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ABSTRACT

A study analyzed in detail the perspectives in science and mathematics literacy found in the national standards for science and mathematics. The National Science Education Standards (NSES), the Benchmarks for Science Literacy, the Curriculum and Evaluation Standards for School Mathematics, and the Professional Teaching Standards for School Mathematics were analyzed using a consensus-building iterative process to identify those standards that address communication (speaking, listening, reading and writing) and reasoning. Results indicated that the standards documents examined proposed similar perspectives on literacy that differed, however, in significant ways. The Benchmarks for Science Literacy give greater emphasis to knowing principles than to the application of principles, while the Curriculum and Evaluation Standards for School Mathematics emphasize the reverse. The NSES overall emphasizes the knowing of principles, but not when just the communication and reasoning components are considered. The NSES contains the most detailed description of ordinary literacy based in the discipline of science or mathematics, while the view of ordinary adult science and mathematics literacy held by framers of the Mathematics Standards and the Benchmarks must be inferred. In many respects statements in the standards documents about literacy are clear and reasonable. However, for curriculum and test designers, standards relating to literacy are open to wide interpretation. (Contains 35 references, 10 endnotes, and 11 tables of data. Appendixes contain lists of components of the standards analyzed as they relate to communication and reasoning.) (RS)

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LITERACY IN THE NATIONAL SCIENCE AND MATHEMATICS STANDARDS: COMMUNICATION AND REASONING

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The Center on English Learning & Achievement (CELA) is a national research and development center located at the University of Albany, State University of New York, in collaboration with the University of Wisconsin-Madison. Additional research is conducted at the Universities of Oklahoma and Washington.

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INTRODUCTION

Leaders from all sectors of society are calling for high school graduates who are science and mathematics literate[1], individuals who can participate intelligently and productively in the performance of their civic, economic, and personal responsibilities. National standards sketch the nature of science and mathematics knowledge and abilities that characterize the literate person as well as the nature of teaching, assessment practices, and the responsibilities of organizations and individuals across the wider system that will enable achievement of the Third and Fourth National Educational Goals. States and local districts across the nation are adapting these national standards and addressing the formidable task of creating the educational environments in which science and mathematics literacy can be achieved.

This paper analyzes in detail the perspectives on science and mathematics literacy found in the national standards for science[2] and mathematics[3]. The results of the analysis will inform efforts to practice science and mathematics education in ways that will produce a more science literate citizenry. While our project's primary focus is on improving assessment practices, we see assessment and teaching as two sides of the same coin and believe that assessment broadly defined informs standards-based program and course development and classroom practices (Champagne, 1996).

Our analysis of science and mathematics literacy is influenced by the location of our project[4] in the U.S. Department of Education-sponsored National Research Center on English Learning & Achievement. Integration of our science and mathematics work into the cross-disciplinary perspectives of the Center's work requires that we situate our work within the highly sophisticated perspectives on literacy held in English education. Further, we link our work with the every-day perspective on literacy held by educators across disciplinary fields. Our theoretical perspective is cognitive. Our analysis of literacy gives consideration to the information stored in memory, its structural organization and the cognitive processes that operate on that information.

General Definitions of Literacy and Relation to Science and Mathematics Literacy

Prior to examining definitions of literacy contained in the science and mathematics standards, we examined some particulars of a general definition of literacy. Commonly, literacy is defined in terms of its component abilities: reading, writing, listening, and speaking. Definitions of literacy often go beyond the abilities to read, write, listen and speak to include the abilities to communicate and reason.

Communication implies some degree of understanding. Reading and listening can occur without an understanding of the message the text or speech was intended to convey. Speech and text may not be understood by the intended audience. Communication occurs when the listener or reader understands the information the speaker or writer intended to convey.

Literacy implies the ability to connect ideas coherently with a purpose in mind. Langer, Applebee & Nystrand (1995) distinguish this "rethinking" or "reformulating" aspect of literacy from the notion of literacy as basic reading and writing skills (p. 3). In addition to learning the basic literacy skills to "get by," literacy at higher levels involves "the kinds of reflective and analytic activities that support successful learning and communication" and that are the result of "the ability to use language, content and discourse to extend meaning and knowledge about ideas and experiences" (p. 3). The Langer, Applebee & Nystrand (1995) perspective on literacy is sociocognitive. "Students can gain high literacy because it is an integral part of the cultural way of knowing and doing that underlies how [a school] class operates and work gets done" (p. 71).

Thus, literacy beyond a basic level involves the ability to use language, content and thinking from various perspectives in situationally aware, purposeful ways to make sense of experience and gain ideas.

For science and mathematics, the purposeful thinking that underlies literacy beyond a basic level implies scientific reasoning, reasoning that produces convincing arguments. We may think of this as one definition of "reasoning."[5] Thought and logic in science and mathematics have a strong association: "Until the twentieth century, logic and the psychology of thought were often considered one and the same. The Irish mathematician George Boole (1854) called his book on logical calculus *An Investigation of the Laws of Thought*, and designed it 'in the first place', to investigate the fundamental laws of those operations of mind by which reasoning is performed" (Anderson, 1990, p. 291).

Inferences about a person's abilities to read, listen, speak, write, communicate and reason are based on observations of individuals' actions and the products[6] produced by those actions. When we observe an individual responding to a sign or an oral command with an action consistent with the message in the sign or the command, we infer that the person has the ability to read or listen. If, however, the person does not respond with an action that is consistent with the sign or command, we cannot be sure that the person cannot read or listen. The person may be able to read or to listen but not understand the sign or the command. Or, the person may understand and choose not to respond to the message conveyed in the sign or command. A sample of speech or a sample of text are examples of products that signal the abilities to speak and write. Based on observations of actions and products, we make inferences about far more than whether or not a person can read, write, speak, listen or communicate. We also make judgments about what the person knows and how the person reasons.

In our everyday lives we make inferences about the quality of a person's reasoning based on his or her speech and writings. If we judge that an argument is logical, we conclude that the person reasons logically. If we judge that the information an individual uses is accurate and congruent with the person's age and intellectual level, we make assumptions about the quantity, quality, and organization of the information stored in the person's memory. We make judgements about literate behavior based on our personal internal standards about appropriate levels of literacy. These standards, rather than explicit, are based on the age, background and education of

the individual. Minimal literacy is based on relatively simple and generally agreed-upon criteria, the abilities to sign one's name and read simple text. The criteria that define the degree or level of literacy (i.e., literacy beyond the basic level) are more vague.

Venesky (1990) defines three levels of literacy: learned, competent, and capable of minimal function. Venesky's levels, which apply in both personal and professional contexts, are not distinct but identify points along a continuum. For instance, physicians' medical literacy ranges from capable of minimal function in the profession (no malpractice suits) to learned (the holder of a distinguished chair of medicine). In the personal context, literacy ranges from a capability for minimal function in society (earning a living, voting regularly, attending to health matters) to functioning as a learned participant (a national leader serving as chair of a foundation).

In educational contexts, the literacy continuum is tied to years of education and the developmental levels of students. The literacy level expected of students who graduate from high school is lower than that of a two or four year college graduate. In higher education, the expectations for general literacy for students in liberal education programs is essentially uniform across majors or professional education programs. However, the disciplinary or professional literacy expectations differ across majors, as well as across schools within higher education, for instance in colleges of arts and sciences and professional schools of business, education, or medicine.

There are different types of literacy. Literacy may be ordinary, the literacy applied by ordinary people in the daily activities of life; profession specific, the literacy required for performance in a profession; or domain specific, the literacy possessed by individuals practicing inquiry in the disciplines. Science, mathematics, historical, political, computer and cultural are examples of domain specific literacies. These literacy types are characterized by different information bases, forms of reasoning and methods of professional practice, or modes of inquiry. The domain-literate person has a store of information about the domain: factual information, concepts, principles, laws, modes of reasoning, and methods of inquiry.

Domain specific, ordinary, and profession specific types of literacy have elements in common. The domain (biology) or professionally (medicine) literate person is also literate in the ordinary sense. Physicians have some of the domain specific knowledge and reasoning abilities characteristic of the biologist and chemist. The person who is literate in the ordinary sense may

have some domain specific knowledge and abilities. The contemporary call for science and mathematics literate citizens implies science and mathematics literacy in the ordinary sense, that is, knowing enough science and mathematics to participate actively and intelligently in the work place and in civic affairs. The literacy picture is further complicated by the fact that not only are there different types of literacies, but within each type there are different literacy levels. For instance, ordinary citizens have very different levels of science literacy ranging from little to a level close to that of a practicing scientist. Ordinary citizens also have different levels of mathematics literacy ranging from vocabulary and reasoning related to simple arithmetic to that related to complex axiomatic systems.

Literacy has performance and cognitive components. Performance components are those observable things the literate person can do. Cognitive components are the cognitive processes and information underlying performance. The cognitive components are inferred from observations of performance. Our analyses of science and mathematics literacy, which are domain literacies, touch on the different features and facets of literacy.

Literacy as Defined in the Science and Mathematics National Standards

Science Literacy

Two professional societies, the American Association for the Advancement of Science (AAAS) and the National Research Council (NRC) have produced national standards for science education. The AAAS standards are contained in a document titled, *Benchmarks for Science Literacy* (AAAS, 1993). The NRC standards are contained in a document titled, *National Science Education Standards* (NRC, 1996).

The *Benchmarks for Science Literacy* (AAAS, 1993) promote literacy in science, mathematics, and technology:

> In a culture increasingly pervaded by science, mathematics, and technology, science literacy requires understandings and habits of mind that enable citizens to grasp what those enterprises are up to, to make some sense of how the natural and designed worlds work, to

> think critically and independently, to recognize and weigh alternative explanations of events and design trade-offs, and to deal sensibly with problems that involve evidence, numbers, patterns, logical arguments, and uncertainties. (p. XI)

While supportive of a common core of learning in science, mathematics and technology, the authors of the *Benchmarks for Science Literacy* (AAAS, 1993) have a particular vision for that core and state that the core should "center on science literacy, not on an understanding of each of the separate disciplines" (p. XII). They also state that "the core studies should include connections among science, mathematics, and technology and between those areas and the arts and humanities and the vocational subjects" (p. XII).

The *National Science Education Standards* (NRC, 1996) document asserts the practical utility and aesthetics of scientific literacy, describes the characteristics of science literate persons, and states that the content standards[7] define scientific literacy:

> Scientific literacy is the knowledge and understanding of scientific concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity. It also includes specific types of abilities. In the *National Science Education Standards*, the content standards define scientific literacy. (p. 22)

The attributes of the science literate adult are described in terms of abilities. The science literate person can:

- find or determine answers to questions derived from curiosity about everyday experiences
- describe, explain and predict natural phenomena
- read with understanding articles about science in the popular press and engage in social conversation about the validity of the conclusions
- identify scientific issues underlying national and local decisions
- express positions that are scientifically and technologically informed
- evaluate the quality of scientific information on the basis of its source and methods used to generate it
- pose and evaluate arguments based on evidence and apply conclusions from such arguments appropriately
- appropriately use technical terms (NRC, 1996, p.22)

The content standards which define scientific literacy are sorted into nine clusters: Unifying Concepts and Processes; Science as Inquiry; Physical Science; Life Science; Earth and Space Science; Science and Technology; Science in Personal and Social Perspectives; and the History and Nature of Science. With the exception of the Unifying Concepts and Processes Standards, the

standards are sorted further by grade level: K-4, 5-8, and 9-12. Standards in each content/ level cluster contain two to five general statements about the ideas and abilities students should develop as a result of their science education. Each standard is elaborated in two sections that follow the standard statement. One, Developing Student Understanding, is an analysis of student learning. The other, Guide to the Content Standard, presents fundamental concepts, principles and abilities that underlie the standard. (NRC, 1996)

Mathematics Literacy

The National Council of Teachers of Mathematics (NCTM) produced three documents presenting national standards for K-12 mathematics education: *Curriculum and Evaluation Standards for School Mathematics* (NCTM, 1989), *Professional Teaching Standards for School Mathematics* (NCTM, 1991) and *Assessment Standards for School Mathematics* (NCTM, 1995).

The Commission on Standards for School Mathematics, established by the Board of Directors of NCTM, was charged with the task of creating "a coherent vision of what it means to be mathematically literate both in a world that relies on calculators and computers to carry out mathematical procedures and in a world where mathematics is rapidly growing and is extensively being applied in diverse fields." (NCTM, 1989, p. 1) In response to that task and a second one of creating a set of standards to guide the reformation of school mathematics, the Commission produced the *Curriculum and Evaluation Standards for School Mathematics* (NCTM, 1989), which contains 13-14 standards each for grades K-4, 5-8 and 9-12. Reasoning and communication are two of the four standards that form a common philosophical and pedagogical foundation across all grade levels. The other two focal standards are connections (within mathematics and to other subject areas) and problem solving.

Although mathematical literacy is not directly defined within the *Curriculum and Evaluation Standards for School Mathematics*, the authors' identify their vision of mathematics literacy as based on a reexamination of educational goals:

Historically, societies have established schools to --

- transmit aspects of the culture to the young;
- direct students toward, and provide them with, an opportunity for self-fulfillment.
- Thus, the goals all schools try to achieve are both a reflection of the needs of society and the needs of students.

Calls for reform in school mathematics suggest that new goals are needed. All industrialized countries have experienced a shift from an industrial to an information society, a shift that has transformed both the aspects of mathematics that are needed to be transmitted to students and the concepts and procedures they must master if they are to be self-fulfilled, productive citizens in the next century.

. . . The educational system of the industrial age does not meet the economic needs of today. New social goals for education include (1) mathematically literate workers, (2) lifelong learning, (3) opportunity for all, and (4) an informed electorate. (NCTM, 1989, pp. 2-3)

The goal that most directly addresses mathematics literacy is the need for mathematically literate workers. According to the *Curriculum and Evaluation Standards*:

The U.S. Congressional Office of Technology Assessment (1988) claims that employees must be prepared to understand the complexities and technologies of communication, to ask questions, to assimilate unfamiliar information, and to work cooperatively in teams. . . . Henry Pollak (1987), a noted industrial mathematician recently summarized the mathematical expectations for new employees in industry:

- The ability to set up problems with the appropriate operations
- Knowledge of a variety of techniques to approach and work on problems
- Understanding of the underlying mathematical features of a problem
- The ability to work with others on problems
- The ability to see the applicability of mathematical ideas to common and complex problems
- Preparation for open problem situations, since most real problems are not well formulated
- Belief in the utility and value of mathematics (NCTM, 1989, pp. 3-4)

The *Professional Teaching Standards for School Mathematics* (NCTM, 1991) addresses the teaching environment needed to achieve the vision outlined in the *Curriculum and Evaluation Standards*; however, the nomenclature shifts from a focus on "mathematics literacy" to a focus on "mathematical power." Components of literacy are embedded in the abilities needed to attain mathematical power:

Mathematical power includes the ability to explore, conjecture, and reason logically; to solve nonroutine problems; to communicate about and through mathematics; and to connect ideas within mathematics and between mathematics and other intellectual activity.

Included among the proficiencies that the *Professional Teaching Standards* delineate for

teachers is that of "orchestrating classroom discourse in ways that promote the investigation and growth of mathematical ideas." (NCTM, 1991, p. 1) Classroom discourse emerges as the dominant communication theme in the *Professional Teaching Standards for School Mathematics*, as evidenced by the fact that three out of the six standards for teaching mathematics involve discourse:

Standards for Teaching Mathematics

- Worthwhile Mathematical Tasks
- The Teacher's Role in Discourse
- The Students' Role in Discourse
- Tools for Enhancing Discourse
- Learning Environment
- Analysis of Teaching and Learning (NCTM, 1991, p. V)

Throughout the *Professional Teaching Standards for School Mathematics* there is an emphasis on shifting from the notion of classrooms as collections of individuals toward classrooms as mathematical communities engaging in spoken and written discourse about and with mathematics.

The *Assessment Standards for School Mathematics* (NCTM, 1995) continues the perspective established in the *Professional Teaching Standards* of looking at mathematics literacy in terms of "mathematical power":

> In the NCTM's Standards documents, the phrase mathematical power has been used to capture the shift in expectations for all students. The shift is toward understanding concepts and skills; drawing on mathematical concepts and skills when confronted with both routine and nonroutine problems; communicating effectively about the strategies, reasoning, and results of mathematical investigations; and becoming confident in using mathematics to make sense of real-life situations. It is away from mastering a large collection of concepts and skills in a particular order. (NCTM, 1995, pp. 2-3)

From this perspective, mathematics literacy can be achieved through systematic shifts in a number of aspects of schooling, including:

> A shift in the vision of learning mathematics toward investigating, formulating, representing, reasoning, and applying a variety of strategies to the solution of problems -- then reflecting on these uses of mathematics -- and away from being shown or told, memorizing, and repeating. This represents a shift from mechanical to cognitive work and also assumes the acquisition of a healthy disposition toward mathematics. Furthermore, cognitive work for all students is culturally dependent because students bring to each lesson their past experiences and the diverse facets of their cultural identities. (NCTM, 1995, p. 2)

Paramount in the *Assessment Standards*, as evidenced by the latter part of the previous quote, is the notion that there may be a cultural aspect to mathematics literacy that allows for and capitalizes on diversity.

The mathematics and science standards contain more detailed information about the communication and reasoning abilities expected of students[8] than the definitions of mathematical and science literacy that introduce them. The standards imply that literacy involves both knowing about scientific and mathematical facts, concepts, principles, laws, theories and modes of inquiry as well as the ability to reason scientifically and mathematically. While we acknowledge the important contribution of both knowing about science to science literacy and of knowing about mathematics to mathematics literacy, our analysis of the standards documents focuses on communication (reading, writing, listening and speaking) and reasoning.[9] We organized our investigation around four main questions:

- What proportion of the science and mathematics standards address communication and reasoning?
- What is the distribution of communication and reasoning concepts, principles and abilities (components of standards) across documents and grade levels in the national science and mathematics standards?
- What are the implied levels of communication and reasoning in the national science and mathematics standards?
- What are the implications of our findings for the practice of science and mathematics education?

METHOD

The *National Science Education Standards (NRC, 1996)*, the *Benchmarks for Science Literacy* (AAAS, 1993), the *Curriculum and Evaluation Standards for School Mathematics* (NCTM, 1989), and the *Professional Teaching Standards for School Mathematics* (NCTM, 1991) were analyzed using a consensus-building iterative process, to identify those standards that address communication (speaking, listening, reading and writing) and reasoning. The *National Science Education Standards* (NRC, 1996), the *Benchmarks* (AAAS, 1996) and the *Curriculum and Evaluation Standards for School Mathematics* (NCTM, 1989), as the science and mathematics

documents with the greatest proportion of standards addressing communication and reasoning, were further analyzed to identify any overt or implied differentiation in the levels of expected performance in meeting the communication and reasoning standards.

Unit of Analysis

Our objective was to identify expectations for science and mathematics literacy contained in the standards documents and to calculate the proportion of the total standards that addressed components of literacy. Because each of the documents has a different format, our first challenge was to identify the portions of the documents that we would search. Table 1 delineates each of the major sections of the standards documents. Those sections in **bold** contain explicit expectations for student attainment. For each section analyzed, an example of the form in which the standard is presented is provided. That portion of the standard that was included in the total count used to calculate the proportion is ***italicized and boldfaced***.

Analytical Method

The analysis of the standards documents was conducted by five individuals. Three of the investigators were primarily mathematics educators; two were primarily science educators. Each of the five individuals independently searched portions of the documents for expectations for student performance related to communication, writing, reading, and reasoning. The results of the independent analyses were compared and discussed by the five investigators. As a result of these discussions the guidelines for searches were further defined and applied to a second round of analysis of that section. Our search was guided by the following definitions of communication and reasoning: Communication -- any means of expressing ideas via use of language, diagrams or symbols; Reasoning -- the connection of ideas consciously, coherently and purposively, thinking in logical form, and justifying or explaining. More specifically, the kinds of expectations that guided our search included:

Reading/Listening -- references to the abilities to make judgments about the scientific or mathematical accuracy of text or to judge the quality of argumentation presented;

Writing -- references to the ability to write explanations meeting criteria for scientific or mathematical explanations;

Communication -- references to the actions of conveying meaning from one person to another, as well as knowing about the place of communication in scientific and mathematical inquiry and the communities of scientists and mathematicians; and

Reasoning -- references to the ability to reason in mathematically and scientifically sound ways.

Expectations identified in the standards generally were of three types:

concept -- a construct, a single general or specific idea;

principle -- a statement of relationships between two or more concepts; or

ability -- an acquired proficiency, often associated with a cognitive or overt action .

Examples of each of these from the *National Science Education Standards* (NRC, 1996) are:

Concept:	Evidence and Explanation
Principles:	Scientific explanations emphasize evidence, have logically consistent arguments, and use scientific principles, models and theories. Arguments must be logical and demonstrate connections between natural phenomena, investigations and the historical body of scientific knowledge.
Abilities:	Recognize and analyze alternative explanations. Communicate and defend a scientific argument.

Only the Unifying Concepts and Processes Standards of the *NRC* Content Standards contain single concepts as standards. The other mathematics and science standards contain concepts only as components of principles.

The total number of concepts, principles and abilities in the standards were determined as follows:

- Each concept, principle and ability was identified
- Each concept, principle or ability was counted at least once
- Each principle was counted only once

- For the most part, abilities were counted once. However, if the ability contained multiple reasoning or communication actions, as was often the case in the *National Science Education Standards*, the number of actions determined the count. For example: "Think critically and logically to make the relationship between evidence and explanations" (NRC, 1996, p. 145) was counted as two abilities -- think critically and think logically.

Note that only thirteen concepts appear in our analysis. These unifying concepts are the only concepts listed in the standards as concepts. All other concepts are elements of fundamental principles. "Sound is produced by vibrating objects" is an example of a principle contained in the K-4 content standards (NRC, 1996, p. 127). Even though the statement contains two concepts, sound and vibrating objects, it was counted only as a principle in our analysis. To obtain a rough estimate of the total number of concepts in the standards, multiple the number of principles by 2 and add 13.

RESULTS

Proportion of Science and Mathematics Standards Addressing Communication and Reasoning

The first question we addressed was the relative percent of emphasis on communication and reasoning in the national science and mathematics standards. The emphasis appears greater in the NCTM mathematics standards documents (45 percent for the *Curriculum and Evaluation Standards* and 23 percent for the *Professional Teaching Standards*) than in the NRC and AAAS science documents (14 percent each for both the NRC content and teaching standards and 10 percent for the AAAS *Benchmarks* [see Table 2]). (For a listing of the components that relate to communication and reasoning, see Appendix A for the NRC Content Standards, Appendix B for the NRC Teaching Standards, Appendix C for the AAAS *Benchmarks*, Appendix D for the NCTM *Curriculum and Evaluation Standards*, and Appendix E for the NCTM *Professional Teaching Standards*.)

Although all the NRC *National Science Education Standards (NSES)* standards for content, teaching, professional development, assessment, education program, and education systems were

reviewed, only standards for content and teaching directly address communication and reasoning. Standards for assessment, program and system do not contain communication and reasoning expectations for students. However, text elaborating the assessment standards define criteria that should be used to judge the quality of student performance. For instance, criteria for judging the quality of scientific explanations are contained in the elaborating text for the assessment standards. The NCTM *Assessment Standards* also do not contain standards directly addressing communication and reasoning but focus more on general goals and the design of assessment.

Distribution of Concepts, Principles and Abilities across Documents and Grade Levels

The second question that we addressed in our investigation was the distribution of communication and reasoning concepts, principles and abilities (components of standards) across documents and grade levels in the national science and mathematics standards.

The NRC *NSES* Content Standards, the AAAS *Benchmarks*, and the NCTM *Curriculum and Evaluation Standards* allowed for a breakdown of the components of the standards into concepts, principles and abilities. For both science and mathematics the teaching standards were constructed with regard to teacher actions and do not lend themselves to this finer level of analysis.

An examination of the distribution of concepts, principles and abilities across documents revealed that the NRC, AAAS and NCTM standards documents differ in the amount of weight given to knowing principles versus the ability to apply the principles (see Table 3). The full NRC *NSES* Content Standards consist primarily of principles (271) rather than abilities (49), which demonstrates that more weight has been placed on knowing scientific principles. However, when examining just the principles and abilities identified as addressing communication and reasoning, a different picture emerges. Of the 49 concepts, principles and abilities addressing communication and reasoning, 19 are principles and 28 are abilities. Thus, within the reasoning and communication context, there is a greater emphasis on abilities than on principles.

Overall, the AAAS *Benchmarks* demonstrate a strong emphasis on knowing scientific principles, with a ratio of principles to abilities of 769 to 87. In the general context of the document, one can see the importance the authors place on knowing scientific concepts, scientific inquiry, and the principles connecting science to mathematics and technology. However, as was the case with

the NRC content standards, when only the reasoning and communication principles and abilities are considered, the ratio of principles to abilities approaches a more even distribution -- 57 to 32. However, unlike the NRC *NSES* Content Standards, the principles in raw number still outweigh the abilities. Thus in the context of the two sets of science standards, the reasoning/communication components of literacy have distinct knowledge components. In one instance the reasoning/ communication components are associated with knowledge about scientific principles; whereas in the other, the reasoning/ communication components are associated with knowledge about the form and attributes of scientific communication and reasoning used in the application of principles.

The NCTM *Curriculum and Evaluation Standards* differ overall from both the science standards documents in that the total standards components favor abilities over principles, with 260 of the 277 components referring to abilities. This emphasis is maintained in the components addressing just communication and reasoning, with 117 of the 122 components referring to abilities. Thus the same distinction between knowing about the knowledge products of the discipline -- in this case mathematics -- as a component of literacy, in contrast with knowing about the form and content of mathematical reasoning, is evident in the NCTM *Curriculum and Evaluation Standards*.

An examination of the distribution of concepts, principles and abilities across grade levels in the documents (see Table 4) revealed a relatively equal distribution across grade levels. It also was clear that both knowing (principles) and doing (abilities) are expected at each grade level.

The NRC *NSES* Content Standards contain a total of 13 concepts, 271 principles, and 49 abilities. Of the 13 concepts, two relate to reasoning or communication and are expected to be applied across all grade levels. Of the 271 principles, 19 related to reasoning or communication: three at grade levels K-4, seven at grade levels 5-8, and nine at grade levels 9-12. Of the 49 abilities, 28 relate to reasoning or communication: seven at grade levels K-4, ten at grade levels 5-8, and eleven at grade levels 9-12.

The AAAS *Benchmarks for Science Literacy* contain 769 principles and 87 abilities. Of the 769 principles, 57 relate to reasoning or communication: ten at grade levels K-2, fourteen at grade levels 3-5, fifteen at grade levels 6-8, and eighteen at grade levels 9-12. Of the 87 abilities, 32 relate to reasoning and communication: eight at grade levels K-2, eight at grade levels 3-5, five at grade levels 6-8, and eleven at grade levels 9-12.

The NCTM *Curriculum and Evaluation Standards for School Mathematics* contains 17 principles and 260 abilities. Of the 17 principles, five were related to reasoning or communication: one at grade levels K-4, three at grade levels 5-8, and one at grade levels 9-12. Of the 260 abilities, 117 were related to reasoning or communication: twenty-six at grade levels K-4, thirty at grade levels 5-8, forty-one at grade levels 9-12, and twenty others in the evaluation section.

We included in communication and reasoning abilities those related to mathematical representation and modeling because these actions are integral to mathematical literacy. A mathematically literate person is expected to be able to make sense of mathematics in graphical, diagrammatic, and symbolic forms as well as textual forms. The use of models to describe, interpret, explain and justify within mathematics is considered a major aspect of attaining mathematical power.

Levels of Communication and Reasoning in Science and Mathematics Standards

The third question we considered in our investigation, the implied levels of communication and reasoning in the national science and mathematics standards, required a more narrative-based analysis. We chose the NRC *NSES*, the AAAS *Benchmarks* and the NCTM *Curriculum and Evaluation Standards* as the appropriate documents for this analysis because they broke the standards down into grade levels and directly addressed issues of communication and reasoning.

NRC *National Science Education Standards*

While the introduction to the *National Science Education Standards* suggests a unitary view of science literacy, at least three types of science literacy are considered in the document: school life, adult life, and science inquiry. The most detailed description of scientific literacy is contained in the content standards for school students. Certain attributes of the scientifically literate adult functioning in the context of daily life are described in the introduction. And, some of the content standards contain descriptions of attributes that characterize scientists engaged in scientific inquiry. Scientific literacy as it is defined in all three contexts is almost exclusively qualitative. The

quantitative features of science literacy are only hinted at, when the role of mathematics is acknowledged but mentioned only a few times in the fundamental abilities, or principles.

To learn more about literacy levels, we traced component abilities of science literacy across the three types of science literacy to ascertain how the abilities of the science literate adult, students at grades 12, 8 and 4, and scientists engaged in inquiry compare.

Table 5 presents the elements of the NRC *NSES* definition of scientific literacy and the attributes of the scientifically literate adult and identifies which of these are elements of ordinary literacy. Adult literacy has both knowledge and ability components. The ability components are related to doing science and to science in life's activities. Table 5 illustrates clearly that elements of ordinary literacy -- the abilities to read, speak, engage in discourse, write, compose arguments and use scientific vocabulary -- are integral to the activities of daily life.

The understanding- and doing-science elements of adult literacy also appear in the content standards for students. However, the science-in-life's-activities elements do not appear in the content standards for students. Thus, while the value of adult science literacy is established in the context of life's activities, students' literacy is centered primarily in doing school science and doing school engineering, that is, designing solutions to practical problems. Three abilities related to communication and reasoning are emphasized in the NRC *NSES* Content Standards. These are developing explanations, using evidence, and questioning. These abilities appear in the descriptions of the adult literacy and the K-12, 5-8, and K-4 student abilities; and they are mentioned as attributes of scientists' literacy (See Tables 6-8).

Explanation. Explanation is a central construct related to communication in the NRC *NSES*. According to the NRC *NSES* document:

> Scientific explanations incorporate existing scientific knowledge and new evidence from observations, experiments, or models into internally consistent logical statements. Different terms such as "hypothesis," "model," "law," "principle," "theory," and "paradigm" are used to describe various types of scientific explanations. As students develop and as they understand more science concepts and processes, their explanations should become more sophisticated. That is, their scientific explanations should more frequently include a rich scientific knowledge base, evidence of logic, higher levels of analysis, greater tolerance of criticism and uncertainty, and a clearer demonstration of the relationship between logic, evidence and current knowledge. (NRC, 1996, p. 117)

Explanation as a component of adults', students', and scientists' literacy is summarized in Table 6. Differences in levels of expectations across the grade levels are not well defined.

Students at grades 4 and 8 are expected to construct and communicate explanations. Inferring the essential differences between construct and communicate is left to the reader, as is inferring the characteristics of a *reasonable* explanation or the appropriate use of evidence in constructing an explanation.

It is in the context of explanation that reasoning is explicitly addressed in the content standards. Logic, logical thinking and critical thinking are mentioned only in the Grade 8 content standards. These modes or reasoning are not defined. Neither are essential similarities and differences between them presented or how students' use of these modes of reasoning might be inferred from the explanations they construct.

Analysis, an ability requiring formal modes of thinking, is a reasoning expectation of students in grades 8-12. Here again inferring the level of analysis expected at the two grade levels is left to the reader.

Evidence. Evidence is another important construct in the NRC *NSES* definition of scientific literacy. According to the document:

> Evidence consists of observations and data on which to base scientific explanations. Using evidence to understand interactions allows individuals to predict changes in natural and designed systems. (NRC, 1996, p. 117)

The use of evidence is mentioned as an element of adult literacy, as an element of student literacy at all three grade levels, and as an attribute of scientists practicing scientific inquiry (See Table 7).

The NRC *NSES* provides a definition of evidence, calls for its use by students in explanations, and indirectly asserts its use by scientists in the process of developing explanations. The K-4 abilities elaboration states that, "Even at the earliest grade levels, students should learn what constitutes evidence and judge the merits or strength of the data and information that will be used to make explanations." (p. 122) And the 9-12 principles mention the rules of evidence. However, the *NSES* provides little information about matters related to the appropriateness of evidence, its quality, or the rules that govern its use.

Questioning. We have included abilities related to questioning in communication and reasoning in our classification of components of the standards. Even though the questioning abilities do not reference communication or reasoning explicitly, we included them because of their relationship with investigation and experimentation, specifically, hypothesis generation and

appeal to evidence. Furthermore, according to the NRC *NSES*, questioning is an attribute of communication among scientists

Questioning abilities across all three types of science literacy are illustrated in Table 8. Little is said about the qualities expected of adult questioning ability/questions. At each grade level, however, some elaboration of the fundamental ability is provided. These elaborations provide some information about the expectations for student performance at each grade level. The elaboration of the questioning ability mentions little, if anything, about the intellectual quality of the questions expected for K-4 students and describes in very general terms the approach students might take to find answers to their questions. At grades 5-8, ill-defined questions are mentioned and some text is devoted to the expectation that students at this level should be able to redefine questions to those that can be the focus of scientific investigations. Level 9-12 relates questions/questioning to hypothesis generation and experimental design.[10]

Expectations for reasoning and communication contained in the NRC *National Science Education Standards* leave much to the interpretation of the reader. Consequently they are open to wide interpretation. Furthermore, in the absence of performance standards in the discussion of the standards, the performance of practicing scientists seem to define the performance expectations for students.

AAAS *Benchmarks for Science Literacy*

The abilities addressed by the AAAS *Benchmarks* seem dominated by two large categories. The first may be characterized as the ability to describe. For example, there are several references to describing constructions, observations, graphs, tables, locations, and spatial relationships. References also are made to using statistics and numerical data to describe a variety of experiences and relationships. The second category of abilities is the ability to make critical evaluations of information presented. For example, students are expected to judge the reasonableness of answers, criticize the reasoning in arguments, and suggest alternate ways of explaining as part of criticizing arguments.

The AAAS *Benchmarks* are as open to interpretation as the NRC *NSES* Content Standards. In

a few instances, increasing complexity across grade levels is more evident in the AAAS *Benchmarks* than in the NRC *NSES* Content Standards.

NCTM *Curriculum and Evaluation Standards for School Mathematics*

Each of the grade level divisions (K-4, 5-8, and 9-12) as well as the evaluation section of the NCTM *Curriculum and Evaluation Standards for School Mathematics* contains components under the general standard headings of Communication and Reasoning. These sections were examined in detail for descriptions of the nature or level of performance expected of students in meeting these standards. To facilitate the analysis and discussion, we sorted the components of these standards into groups according to common content within the standards.

Communication. We identified five major groupings for the components of the standards on Communication (see Table 9) that we labeled as: Reflection and Clarification; Attitude or Affect, Presentation, Language, and Critical Analysis. Any component from the evaluation section of the NCTM *Curriculum and Evaluation Standards for School Mathematics* seemed to serve as an effective summary for the grouping in which it appeared.

Reflection and Clarification. All three grade-level divisions (K-4, 5-8, and 9-12) contain nearly identically worded components regarding reflection on and clarity of thinking about mathematics; however, there is no parallel standard in the evaluation section. At levels K-4 and 5-8, clarity and reflection are to be applied to mathematical ideas and situations; whereas at level 9-12, the clarity and reflection are applied to mathematical ideas and relationships. One might infer that in grades 9-12 there is a greater expectation that students be able to demonstrate the ability to think in highly literate ways not just about the mathematical ideas but about the relationships among those ideas, while K-8 students are expected to demonstrate the ability to think in highly literate ways about ideas and situations but not necessarily about the relationships.

Attitude or Affect. The second group of components addresses issues of attitude and affect in the form of valuing and appreciating mathematics. The focus at the K-4 level is on realizing that communication, in many forms, is a vital part of mathematics. At the 5-8 and 9-12 levels, the focus shifts to a narrower emphasis on appreciating the role of mathematical notation, with the 9-12

students expected to frame their appreciation within a sophisticated, systemic context of economy, power and elegance. The text accompanying the components of the Communication standard at grades 9-12 further states that college-intending students should use more sophisticated notation (NCTM, 1989). It appears then, that greater rigor in notation is expected at the higher grade levels than at the primary levels, with the highest level expected of college-intending students.

Presentations. The group of components addressing issues of presentation as part of communication are characteristic of three dimensions: a) a two-factor dimension related to the elements of literacy -- reading/writing versus listening/speaking; b) a two-factor dimension of content -- ideas versus relationships; and c) a three-factor dimension on mode of representation -- physical, pictorial, and abstract. All three dimensions are evident in the two relevant components from the evaluation section. Also, at all levels, students are expected to communicate orally and in writing. This is not evident in the actual component for grades K-4; but the text that accompanies that component stresses the need and value of involving young children in both "talking mathematics" and writing about mathematics. (pp. 26-28) The relevant presentation component from grades K-4 addresses modes of representation and reveals the expectation that K-4 students will master physical and pictorial aspects of mathematical ideas, leaving the abstract to be attained in grades 5-12. The 5-8 component supports this, specifying that 5-8 students are expected to model situations using graphical and algebraic methods as well as concrete and pictorial. The 9-12 component is stated generally without specifying the content or the mode. We assume that expectations for this grade level include those for previous grades unless otherwise stated. One of the evaluation components in this third group indicates that vocabulary, notation, and structure should be used to describe relationships. Describing relationships is not mentioned in any of the grade-level specific components in this group. However, because "relationships" was a concept that appeared at grades 9-12 for Reflection and Clarification, we assumed the description of relationships was intended for students in grades 9-12.

Language. The fourth group of components focuses on the development of meaningful language for mathematics. Students in grades K-4 are expected to relate their everyday language to mathematical language and symbols. The inclusion of symbols at this level, taken together with the lack of mention of symbols or abstraction for K-4 students in the previous group of presentation components, clarifies the expectation that students are to learn mathematical symbols in a

meaningful context before using them extensively. At grades 5-8, students are expected to develop common understandings of mathematical ideas and definitions, as well as understand the role of definition. The notion of developing a common understanding implies that a community of learners works together to achieve this, rather than having definitions authoritatively delivered for memorization. At grades 9-12, students are expected to take a next step in the development of meaningful language in applying the use of definitions and language to express generalizations discovered through investigations.

Critical Analysis. The fifth group of communication components are critical analysis skills for mathematics consistent with the definition of high levels of literacy stated by Langer, Applebee and Nystrand (1995). The intellectual processes of interpreting, evaluating, conjecturing, arguing, clarifying, and reading with understanding often require the integration of different perspectives and different ways of thinking and communicating. Although K-4 students may be able to do some of this, these aspects of literacy are not expected to be attained consistently until grades 5-12. There seems to be little distinction between expectations for grades 5-8 versus grades 9-12 on these components. However, examples provided in the NCTM *Curriculum and Evaluation Standards for School Mathematics* of possible approaches to tasks (NCTM, 1989) indicate that these aspects are expected to develop over time as a result of a progression of explorations of concepts, with college-intending students expected to show greater sophistication than other students.

Reasoning. Although the components from the Reasoning standards did not group along dimensions as the Communication components did, they addressed two different aspects of reasoning: a) reasoning actions; and b) types of reasoning. The reasoning actions and the types of reasoning were identified for each component (see Table 10). Then these lists were examined for differences across grade-level divisions.

Reasoning Actions. As with the Communication analysis, the components in the evaluation section serve, to a certain extent, as a summary for the other sections. Overall there is an expected increase in the complexity of reasoning actions that students are able to competently demonstrate across the three grade-level divisions. Reasoning actions expected at grades K-4 include analysis, explanation and justification. At the 5-8 level, more complex reasoning actions are expected: conjecturing, evaluation, argumentation and validation. At grades 9-12, the major shift in expected reasoning actions is the inclusion of proof and the generation of counter-examples. What seems to

be implied throughout the NCTM *Curriculum and Evaluation Standards* is that the ability to generate a reasoned argument is developed over time with increasing levels of rigor. What seems to be missing is a clear identification of the expected nature or level of "correctness" of the reasoning actions. Kuhn (1991) identifies a major difficulty that students have as they "reason." While their actions may take the form of a reasoned argument, students often have difficulty differentiating theories and evidence, and, thus, have difficulty both coordinating the two and seeing beyond a theory to generate a counter-example. For example, when given the problem (Kouba, Zawojewski, & Strutchens, 1997, pp. 119-120):

> Think carefully about the following question. Write a complete answer. You may use drawings, words, and numbers to explain your answer. Be sure to show all of your work.
> Jose ate 1/2 of a pizza.
> Ella ate 1/2 of another pizza.
> Jose said that he ate more pizza than Ella, but Ella said they both ate the same amount.
> Use words and pictures to show that Jose could be right.

one student responded that, essentially, a "half is always a half" and could not get beyond that to even considering the assigned task of showing how Jose could be right. On a four-point scale of incorrect, minimal, partially correct, and satisfactory, the student's answer was scored as "minimal" by a committee of raters. It is not clear in the Curriculum and Evaluation Standards what is to guide a judgment of to what extent this fourth-grade student has attained the reasoning standard.

Types of Reasoning. Regarding types of reasoning, the major shift occurs between the K-4 level and the 5-8 level. At the K-4 level, reasoning is referred to only as logical in a very general sense, as in "draw logical conclusions." The accompanying text (NCTM, 1989, p. 29) explains that this in no way implies that formal reasoning strategies should be taught to K-4 students, rather, they should be encouraged to do the type of reasoning that helps them to see that mathematics makes sense. One can infer, then that the "logical reasoning" implied here is similar to foundational or "transformational reasoning" as described by Simon (1994):

> . . . although inductive and/or deductive reasoning may lead to students persuading themselves of the truth of an idea, that often what they are seeking is not inherently inductive or deductive. Rather they are seeking a sense of how the mathematical system in question works. Such knowledge is often the result of "running" the system, not to accumulate outputs as in an inductive approach, but rather to develop a feel for the system. I call this transformational reasoning. (p. 3)

The reasoning expected at grades 5-12 is expanded to specifically include other types of mathematical reasoning (e.g., spatial and proportional) and formal reasoning (e.g., inductive and deductive). We assume that general or "transformational" reasoning also is expected at these levels. Furthermore, although not specifically stated, but certainly implied in statements about algebraic representation and induction at grades 9-12, there seems to be an expectation of students developing "quantitative reasoning" as defined by Thompson (1993):

> Quantitative reasoning is the analysis of a situation into a quantitative structure -- a network of quantities and quantitative relationships . . . A prominent characteristic of reasoning quantitatively is that numbers and numeric relationships are of secondary importance, and do not enter into the primary analysis of a situation. What is important is relationships among quantities. In that regard, quantitative reasoning bears a strong resemblance to the kind of reasoning customarily emphasized in algebra instruction. (p. 165)

Thus, the nature of the communication and reasoning implied in the NCTM *Curriculum and Evaluation Standards for School Mathematics* is complex, and often implied rather than overtly stated. Unraveling the levels of expectation along grade level or other lines may be an essential step in helping the mathematics education community apply the standards.

Dimensions of Expectations across Standards Documents

When considering how educators are to assess the extent to which curricula and student performance reflect successful achievement of national science and mathematics standards, two dimensions of complexity in the nature of the standards emerge: a cognitive, generative/ evaluative dimension and an observable/inferred dimension. Standards from the NRC *NSES*, the AAAS *Benchmarks*, and the NCTM *Curriculum and Evaluation Standards* may be categorized according to a dichotomous, interactive matrix of these two dimensions (see Table 11).

With regard to the generative/evaluative dimension, science and mathematics curriculums are expected to engage students in varying combinations of two quite different but related cognitive arenas: that of **generating** questions, solutions, explanations, communications and reasoned arguments; and that of **critiquing** such products and actions against the standards of the science and mathematics community. Whereas the cognitive processing associated with the generation of

products and actions theoretically ranges from low to high level, the cognitive processing associated with critique and evaluation is considered exclusively high level. Thus, the nature of the cognitive processing that is stated or implied in a standard can dictate the level of literacy expected.

The generative/evaluative dimension is further complicated by the observable/inferred dimension. Some of the standards are presented in terms of observable actions, whereas others are presented in more subjective terms that require inferences in order to link products and actions with the implied processing. Various levels of performance of a cognitive process such as reasoning logically may be displayed. The standards are open to interpretation regarding which level is expected for whom. Is the presentation of evidence and a conclusion sufficient to indicate logical reasoning, or must a student also provide a justification for the movement from evidence to a conclusion? (Kuhn, 1991) Is an informal justification sufficient, or do certain circumstances and contexts require formal deductive explanations or proof? Such questions raise issues related to practice and policy.

CONCLUSIONS AND IMPLICATIONS

The standards documents examined in this study propose similar perspectives on literacy that differ, however, in significant ways. These differences have important theoretical, curricular, testing and policy implications.

The NRC *NSES* Content Standards focused primarily on science content with scant connections or references to mathematics; the NCTM *Curriculum and Evaluation Standards for School Mathematics* focus primarily on mathematics, with scant reference to connections to science; and the AAAS *Benchmarks* address mathematics, science and technology separately and in combination. These differences in perspective must be kept in mind when looking across the documents for similarities and differences.

In the sections that follow, we address our fourth question concerning implications of our findings for the practice of science and mathematics education, and share just a few of the issues the results of our analysis raise. We label the issues as theoretical, policy, curricular, and testing while recognizing full well that all are intertwined.

A Theoretical Issue

The preceding analysis demonstrates that the AAAS *Benchmarks* give greater emphasis to knowing principles than to the application of principles, while the NCTM *Curriculum and Evaluation Standards* emphasize the reverse. The NRC *NSES* Content Standards overall emphasize the knowing of principles, but reverse that when just the communication and reasoning components are examined. These patterns bring to mind Greeno's (1992) discussion of the two different views about the relation of thinking to classroom learning in science and mathematics: "thinking with the basics" versus "thinking is basic." He states:

> According to "Thinking with the basics," the job of classroom learning is to provide basic scientific or mathematical knowledge that students can then use in thinking mathematically or scientifically after they have learned enough and if they are sufficiently talented and motivated. According to "Thinking is basic," learning to think scientifically and mathematically should be a major focus of classroom activity from the beginning. (p. 39)

It appears that those components of the science and mathematics standards that address communication and reasoning are written from the perspective that "thinking is basic." In considering the implications for classroom activities and for assessment, then, Greeno's propositions and recommendations regarding scientific and mathematical thinking may be equally apt for issues of science and mathematics literacy. The relationship between science and mathematics literacy to the facts, principles, laws, and procedures of the disciplines may be viewed in the same way that Greeno views the relationships of these latter things to scientific and mathematical thinking:

> I propose that we take mathematical thinking and scientific thinking to be activities in which concepts and methods of a mathematical or scientific discipline are used in understanding, including understanding involved in solving a problem. The thing that is understood may be a concept or a problem within the discipline or something outside the discipline whose understanding is informed by the discipline's resources. This view denies that there is mathematical thinking apart from the concepts and methods of mathematics, or that there is scientific thinking apart from the concepts and methods of the various sciences. Indeed, on this view it is more appropriate to talk about thinking within the various fields of science, biological thinking, chemical thinking, physical thinking, cognitive-scientific thinking, and so on, than it is to talk about scientific thinking in general, although there are some significant aspects of thinking that are shared across the scientific disciplines. Even so, I argue that significant mathematical and scientific thinking is done by children, and that the task of school learning should primarily be to strengthen and refine these capabilities, rather than primarily providing knowledge of terms and procedures that are thought to be the materials on which thinking has to be based. (Greeno, 1992, pp. 40-41)

If we take this view, then the 10-14% of the science standards and the 44% of the mathematics standards that address communication and reasoning form an umbrella structure with which to make sense of and interpret the more content oriented components of the standards. Furthermore, in Greeno's examples of students' thinking, students rely on informal reasoning far more than on formal logical reasoning or on algebraic reasoning. As we look at the challenge of assessing to what extent a student or a group of students has attained a standard, we must find ways to describe and understand students' scientific and mathematical reasoning in terms of the students' level of cognition and what can reasonably be expected at a given grade level. Likewise, we must find ways to describe and understand students' perspective on and development of reasoned explanations in light of suggested criteria for high quality arguments. Work such as Damar's (1987) and Kuhn's (1991) on the attributes of argumentation can inform the development and elaboration of criteria for explanations and arguments.

A Policy Issue

The NRC *National Science Education Standards* document contains the most detailed description of ordinary literacy based in the discipline of science or mathematics. The view of ordinary adult science and mathematics literacy held by the framers of the Mathematics Standards and the *Benchmarks* must be inferred from the standards and Benchmarks themselves. The NRC description addresses abilities associated with ordinary literacy, namely the abilities to read, write, speak and engage in discourse about scientific matters in scientifically informed ways. While neither the knowledge about the scientific enterprise and its products nor the character of scientifically appropriate communication and criticisms is explicitly addressed in the *NSES*, knowing about science and its products is a major emphasis of the NRC *NSES* Content Standards and the AAAS *Benchmarks*. The treatment of scientifically appropriate communication and criticism in the NRC *NSES* document is sparse. The AAAS *Benchmarks* contain the more detailed descriptions of the characteristics of scientifically appropriate communication and criticism. The NCTM Standards give approximately equal emphasis to the abilities of communication and knowing about mathematics. However these are defined almost exclusively in the context of school mathematics. If we assume, as it seems reasonable to do, that the framers of the

mathematics and science standards meant the standards for school-leavers to be the standards of literacy for the ordinary citizen, we must conclude that the literacy levels in mathematics and science advocated by the framers of the standards are very high. The ordinary citizen is expected to know a lot of science and mathematics and to be able to reason with and communicate about the knowledge in highly sophisticated ways. As high-stakes national and state tests are developed based on the standards, we must be concerned with how reasonable the standards are. The high level of literacy advocated by the standards has international implications as well. As we compare the performance of U.S. students with those from other countries, we must be mindful of the standards on which a test's performance is based. We must be cautious about celebrating the performance of U.S. students in comparison with those in other countries without knowing if the standards on which the international tests are based are higher, lower, or equivalent to the U.S. standards.

A related policy issue has to do with time. Students can not be expected to develop the sophisticated reasoning and communication skills contained in the mathematics and science standards in a short time or even a year's time. Neither can the fourth, eighth or twelfth grade mathematics teacher be held responsible for teaching five, nine, or thirteen years of reasoning and communication abilities. Even so high-stakes state tests in science and mathematics as well as a high-stakes national mathematics test are being implemented with little consideration to the time it will take for students to develop the literacy abilities called for in the national standards.

Curricular and Testing Issues

Many curricular and related testing issues are provoked by the results of our analysis. Questions of emphasis across the K-12 science and mathematics curriculum with regard to communication and reasoning abilities are central. How do curriculum developers respond to the seeming contradiction in the NRC *NSES* inclusion of general literacy abilities in its treatment of adult science literacy and the considerably lighter treatment of the abilities to read science text critically and to engage in informed discourse about science related issues encountered in their daily lives? Should reading and writing about science and mathematics be a part of the science and mathematics curricula? Is it fair

to test students' understanding of mathematics and science by asking them to read and analyze text about science and mathematics? Should students be required to demonstrate their ability to write about science and mathematics on tests? How will standards of performance for the literacy abilities be set? The science standards provide little guidance on matters such as what constitutes a well-reasoned explanation. Certainly, the reader has questions of his or her own.

In many respects statements in the standards documents about literacy are clear and reasonable. However, for curriculum and test designers standards related to literacy are open to wide interpretation. Consequently students might well be successful in a curriculum designed to meet certain national standards but fail a test designed to measure attainment of the very same standards. Such might well be the outcome, if curriculum design and test development are not well coordinated.

Reasoning as a goal of science and mathematics standards has been an essential theme over many years and remains so in the current standards. The means for realization of that goal in classrooms needs to be revised, especially in the recently emphasized context of better communication and more writing in science and mathematics. Proposing exercises that measure students' attainment of communication and reasoning standards inevitably generates considerable debate among science and mathematics educators whose individual interpretations of the standards are more often than not quite different. The debate illuminates the challenges that teachers must meet in providing students with sufficient opportunity to meet the standards. We know of no better way of answering questions about the meaning of the standards than by developing tasks and being explicit about the kinds of responses that provide convincing evidence that students have met the content standards. Thus, the goal of the next phase of our research is both to explore the development of tasks that require scientific and mathematically literate explanations and to establish means for interpreting and assessing students' responses vis a vis the expectations that teachers and standards authors have for the attainment of communication and reasoning standards in mathematics and science.

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ENDNOTES

1. Mathematics educators often use the single term, *numeracy*, to reference mathematical literacy. Currently there is no clear consensus on the use of the terms. Iddo and Schmitt (1994) indicate that some people prefer one term to the other:

> Some people prefer to use the term "mathematical literacy," believing that "numeracy" is too vague or limiting in scope. Others feel just the opposite, taking "numeracy" to be the mirror image of literacy, and thus a broad concept, while viewing "mathematical literacy" only as a sub-area in mathematics. (p. ii)

Iddo and Schmitt use the terms interchangeably:

> In general, both terms should be viewed as loosely referring to the aggregate of skills, knowledge, beliefs, and habits of mind, and related communicative and problem-solving skills, which individuals may need to effectively handle real-world quantitative situations, problems, and interpretive tasks with embedded mathematical elements. (1994, p. ii)

2. Achieving science literacy for all citizens has long been a goal of science education in the United States. Over the past ten years science literacy has become the central focus of the national standards-based reform movement in science education. National standards for school science education have been developed under the auspices of two professional scientific organizations, the American Association for the Advancement of Science (AAAS) and the National Research Council (NRC) of the National Academy of Sciences (NAS). The same professional organizations have reviewed undergraduate education in the natural sciences, found it wanting, and developed proposals for reforming it.

Setting standards for school science began with the publication by the AAAS of *Science for All Americans*. This document set forth the intellectual and philosophical foundations of Project 2061, the association's premier effort to change the character of science education in the U.S. Following the publication of *Science for All Americans*, two documents were published by the AAAS. *The Liberal Art of Science* is directed to the natural science community in higher education. Its publication was motivated by the recognition that for school science to achieve the changes called for in *Science for All Americans* would also require education in the sciences in the nation's colleges and universities to change. This document defines the knowledge and abilities of the science literate college graduate and suggests how the purposes and pedagogy of undergraduate science education must change if all college graduates, including teachers, are to be science literate. *Benchmarks for Science Literacy* defined the knowledge that characterizes the science literate high school graduate as well as the knowledge that allows schools to benchmark students' progress at grades 2,4, 8, and 12.

Following these publications, the National Research Council of the National Academy of Sciences published *National Science Education Standards*. Contained in this document are a comprehensive set of standards for the practice of science education. Standards for teaching, teacher preparation, assessment, content, and program provide the vision for the practice of science education. System standards define how all organizations and individuals with responsibility for science education must coordinate their efforts if the vision is to be realized. With the publication of *From Analysis to Action: Undergraduate Education in Science, Mathematics and Technology*, the NRC added to the developing literature on scientific literacy. This document contains recommendations for actions to be taken to "equip students with the scientific and technical literacy and numeracy required to play meaningful roles in society." (NRC, 1996, p. 1)

While the documents differ in the elements of science education addressed and in the details of the knowledge and abilities required of the science literate high school graduate, the need for science literacy and the vision of science education contained in them are remarkably similar. The most notable difference

is in the view of inquiry. The *National Science Education Standards* require that students know about inquiry and have the ability to do science inquiry at a level appropriate to their age and professional interests. In contrast, the emphasis in *Benchmarks for Science Literacy* is on knowing about inquiry rather than on the ability to inquire.

The existence of two sets of standards for school science education is a reflection of the vagaries of the recent history of the standards-based reform movement as it is playing out for science education. The two sets of standards reflect the simple fact that no single professional scientific or science education organization is recognized as the leader in U.S. science education. The two sets of science standards challenge science educators at the state, district and classroom levels who are confused about which standards they should follow. The issue is at once political and curricular. Because the subject matter requirements of both sets of standards is so comprehensive and the statements about subject matter so general, subject matter is not as much a curricular challenge as are the abilities to inquire, communicate, and reason. In the case of subject matter, curricula designed using either standards or benchmarks will differ little. What may differ is the time allotted to developing abilities and which abilities -- inquiry, communication, or reasoning -- will be emphased.

3. The development of the National Council of Teachers of Mathematics (NCTM) standards documents is part of the long history of concern for and reform of mathematics education in the United States. Changes in societal needs, schooling policies, economics and technology resulted in changing needs regarding mathematics education. The educational community responded on many fronts including the formulation of reform documents such as the National Advisory Committee on Mathematical Education (1975) report and *An Agenda for Action* (NCTM, 1980). (See Bidwell & Clason, 1970 and Jones & Coxford, 1970 for a description of reform movements and documents prior to 1970). However, the changes in mathematics education of students did not keep pace with the need for mathematically competent citizens, at least according to such reports as *A Nation at Risk* (National Commission on Excellence in Education, (1983) and *Educating Americans for the 21st Century* (National Science Board Commission on Precollege Education in Mathematics, Science and Technology, 1983). In December 1983, a special conference jointly sponsored by the Office of Educational Research and Improvement of the U. S. Department of Education, the National Council of Teachers of Mathematics, and the Wisconsin Center for Educational Research, was held to "a) identify new goals and needed change for school mathematics, and b) to recommend strategies or describe scenarios whereby these goals and changes can be realized." (Romberg & Stewart, 1984, p. 3). The conference was attended by over 40 "mathematicians, mathematics educators, psychologists, computer scientists, state and school mathematics coordinators, mathematics teachers, and publishers of educational texts, tests, and computer software" (p. v) and was chaired by Tom Romberg. The discussions that ensued and the recommendations that resulted from the conference were pivotal in moving the educational community toward the development of the NCTM standards. Other influences on the development of the standards included a strong twenty years of research on students' acquisition of mathematical concepts and the rise of cognitive science as the dominant psychological epistemology.

4. Portions of this report have appeared in papers presented at The College Board National Forum, October 1996, New York City; the international, invited Science Technology and Citizenship Seminar, November 1996, Oslo, Norway; the Globalization of Science Education: International Conference on Science Education, June 1997, Seoul, Korea; and the Seminar on Misconceptions, June 1997, Ithaca, NY.

5. Forty-plus years of research and writing on science literacy has provided an abundance of literature. A search of the ERIC (Educational Resources Information Center) database since its 1966 inception reveals more than 1200 items described by the key term, "scientific-literacy". A further examination using the terms "literacy-" and "science or mathematics or mathematical" will locate at least an additional 2500

items. Even these thousands omit some extremely important science and mathematics literacy documents published prior to 1966 (e.g., seminal publications by P. D. Hurd [1958], and C. P. Snow [1962]). To select and present the documents that define science and mathematics literacy in an historical manner is well beyond the scope of this report and has been done by others before us (e.g., J. D. Miller [1983] and D. A. Roberts [1983]).

6. These products are both verbal, in the form of speech and text, and symbolic, in the form of graphs, equations, diagrams, drawings, and models.

7. The *National Science Education Standards* document organizes the standards for science education in six categories: standards for teaching, professional development, assessment, content, program, and the system.

8. The NCTM Curriculum and Evaluation Standards guide the development of curriculum; however, they are stated in terms of what the curriculum should enable students to do. In that sense, we interpret the standards as being a means also for identifying expectations for student performance and understanding.

9. The many attempts over the years to define science and mathematics literacy have resulted in an understanding of the limitations placed upon such definitions. Any literacy definition is restricted by time, by place, by context, and by additional variables such as levels of literacy or method of literacy measurement. Laugksch (1996, p. 41) reflects these considerations in his definition adapted from Champagne and Lovitts (1989): "Scientific literacy is conceptually defined as a desired level of depth and breadth of scientific understanding appropriate to the interests and needs of the person being taught, set within the context of the developmental, educational, economic, and political needs and interests of a country at a given point in time."

10. Throughout the discussion of questions/questioning, investigations/investigation and experiments/experimentation are used seemingly interchangeably. The document does not address whether investigations and experiments are the same. Because more sophisticated language, such as hypothesis, is used in conjunction with experiment, we might infer that experiment refers to controlled methods of hypothesis testing, while investigation refers to informal observational activities.

Table 1: Documents and Sections Analyzed with Selected Examples

National Science Education Standards

Unifying Concepts and Processes

Content Standards

Example: SCIENCE AS INQUIRY

Content Standard A (K-4)

As a result of activities in grades K-4, all students should develop--

- Abilities necessary to do scientific inquiry
- Understanding about science inquiry

Guide to the Content Standard

Fundamental abilities and concepts that underlie this standard include--

Abilities necessary to do Scientific Inquiry:

- ***Ask a question about objects, organisms, and events in the environment.***
- ***Plan and conduct a simple investigation.***
- ***Employ simple equipment and tools to gather data and extend the senses.***
- ***Use data to construct a reasonable explanation.***
- ***Communicate investigations and explanations.***

Understandings About Scientific Inquiry

- ***Scientific investigations involve asking and answering a question and comparing the answer with what scientists already know about the world.***
- ***Scientists use different kinds of investigations depending on the questions they are trying to answer. Types of investigations include describing objects, events, and organisms; classifying them, and doing a fair test (experimenting).***
- ***Simple instruments, such as magnifiers, thermometers, and rulers, provided more information than scientists obtain using only their senses.***
- ***Scientists develop explanations using observations (evidence) and what they already know about the world (scientific knowledge). Good explanations are based on evidence from investigations.***
- ***Scientists review and ask questions about the results of other scientists' work.***

(NRC, 1996, p. 122-123)

Teaching Standards

Example: Teaching Standard A

Teachers of science plan an inquiry-based science program for their students. In doing this, teachers--

- ***Develop a framework of yearlong and short-term goals for students.***
- ***Select science content and adapt and design curricula to meet the interests, knowledge, understanding, abilities, and experiences of students.***
- ***Select teaching and assessment strategies that support the development of student understanding and nurture a community of science learners.***
- ***Work together as colleagues within and across disciplines and grade levels.***

(NRC, 1996, p. 30)

Professional Development Standards

Example: Professional Development Standard A

Professional development for teachers of science requires learning essential science content through the perspectives and methods of inquiry. Science learning experiences for teachers must--

- ***Involve teachers in actively investigating phenomena that can be studied scientifically, interpreting results, making sense of findings consistent with currently accepted scientific understanding.***
- ***Address issues, events, problems, or topics significant in science and of interest to participants.***

Table 1 (continued)

National Science Education Standards

- ***Introduce teachers to scientific literature, media, and technological resources that expand their science knowledge and their ability to access further knowledge.***
- ***Build on the teacher's current science understanding, ability, and attitudes.***
- ***Incorporate ongoing reflection on the process and outcomes of understanding science through inquiry.***
- ***Encourage and support teachers in efforts to collaborate.*** (NRC, 1996, p. 59)

Assessment Standards
Program Standards
System Standards

Benchmarks for Science Literacy

The Nature of Science
The Nature of Mathematics
The Nature of Technology
The Physical Setting
The Living Environment
The Human Organism

Example: Human Organism: Human Identity
Kindergarten - Grade 2
By the end of the 2nd grade, students should know that--

- ***People have different external features, such as size, shape, color of hair, skin, and eyes, but they are more like one another than like other animals.***
- ***People need water, food, air, waste removal, and a particular range of temperatures in their environment, just as other animals do.***
- ***People tend to live in families and communities in which individuals have different roles.*** (AAAS, p. 128)

Human Society
The Designed World
The Mathematical World
Historical Perspectives
Common Themes
Habits of Mind

Curriculum and Evaluation Standards for School Mathematics

Introduction
Curriculum Standards for Grades K-4

Example: Standard 11: Statistics and Probability
In grades K-4, the mathematics curriculum should include experiences with data analysis and probability so that students can--

- ***collect, organize, and describe data;***
- ***construct, read, and interpret displays of data;***
- ***formulate and solve problems that involve collecting and analyzing data;***
- ***explore concepts of chance.*** (NCTM, p. 54)

Curriculum Standards for Grades 5-8
Curriculum Standards for Grades 9-10
Evaluation Standards
Next Steps

Table 1 (continued)

Professional Teaching Standards for School Mathematics
Introduction
First Steps
Standards for Teaching Mathematics
Example: Standard 2: The Teacher's Role in Discourse The teacher of mathematics should orchestrate discourse by-- • ***posing questions and tasks that elicit, engage, and challenge each student's thinking;*** • ***listening carefully to students' ideas;*** • ***asking students to clarify and justify their ideas orally and in writing;*** • ***deciding what to pursue in depth from among the ideas that students bring up during a discussion;*** • ***deciding when to provide information, when to clarify an issue, when to model, when to lead, and when to let a student struggle with a difficulty;*** • ***monitoring students' participation in discussions and deciding when and how to encourage each student to participate.*** (NCTM, 1991, p. 35)
Standards for the Professional Development of Teachers of Mathematics
Standards for the Support and Development of Mathematics Teachers and Teaching

Assessment Standards for School Mathematics
Mathematics Assessment Standards
Use of the Assessment Standards for Different Purposes
What's Next

Table 2: Relative Percent of National Science and Mathematics Standards Documents Devoted to Communication and Reasoning

Standards Document	Total Components	Communication and Reasoning Components	Percent Communication and Reasoning Components
NRC *NSES*			
Content Standards	333	49	14
Teaching Standards	28	4	14
AAAS			
Benchmarks	856	89	10
NCTM			
Curriculum and Evaluation Standards	260	117	45
Teaching Standards	142	33	23

Table 3: Distribution of Concepts, Principles and Abilities across Standards Documents

	Standards Documents		
	NRC *NSES* Content Standards	AAAS *Benchmarks*	NCTM *Curriculum and Evaluation Standards*
Total Concepts	13	---	---
Communication and Reasoning Concepts	2	---	---
Total Principles	271	769	17
Communication and Reasoning Principles	19	57	5
Total Abilities	49	87	260
Communication and Reasoning Abilities	28	32	117

Table 4: Distribution of Communication and Reasoning Concepts, Principles and Abilities across Grade Levels

	Grade Level			
	K-4	5-8	9-12	All
NRC *NSES* Content Standards				
Concepts	---	---	---	2
Principles	3	7	9	---
Abilities	7	10	11	---
NCTM *Curriculum and Evaluation Standards*				
Concepts	---	---	---	---
Principles	1	3	1	---
Abilities	28	30	41	---
AAAS *Benchmarks*				
Concepts	---	---	---	---
Principles	10	14	15	18
Abilities	8	8	5	11

Table 5: Adult Scientific Literacy in the *NSES*

DEFINITION of SCIENTIFIC LITERACY (*NSES*, 1996, p. 22)	ATTRIBUTES of the SCIENTIFICALLY LITERATE PERSON	ORDINARY LITERACY ELEMENTS
	Doing Science	
knowledge and understanding of scientific concepts and processes	find or determine answers to questions derived from curiosity about everyday experiences;	
	describe, explain and predict natural phenomena	
	Science in Life's Activities	
personal decision making, participation in civic and cultural affairs, and economic productivity	read with understanding articles about science in the popular press;	read
	engage in social conversation about the validity of the conclusions;	engage in discourse
	identify scientific issues underlying national and local decisions;	
	express positions that are scientifically and technologically informed;	speak and write
	evaluate the quality of scientific information on the basis of its source and methods used to generate it;	
	pose and evaluate arguments based on evidence and to apply conclusions from such arguments appropriately;	argumentation
	appropriately use technical terms	vocabulary

Table 6: Explanation in Scientific Literacy in the *NSES*

Adults:	. . . [E]xplain . . . natural phenomena
Students Grades K-4:	Use data to construct a reasonable explanation Communicate . . . explanations
Students Grades 5-8:	Develop . . . explanations using evidence Think critically to make the relationship between evidence and explanations Think logically to make the relationship between evidence and explanations Analyze alternative explanations. . . Communicate scientific . . . explanations
Students Grades 9-12:	Formulate and revise scientific explanations . . . using evidence Formulate and revise scientific explanations . . . using logic Analyze alternative explanations
Scientists:	Formulate and test their explanations Develop explanations using observations (evidence) and . . . Good explanations are based on evidence from investigations. Scientific explanations emphasize evidence, have logically consistent arguments and use scientific principles, models and theories*

*See Appendix A for page references.

Table 7: Evidence in Scientific Literacy in the *NSES*

Adults:	Pose and evaluate arguments based on evidence . . .
Students Grades K-4:	Use data to construct a reasonable explanation.
Students Grades 5-8:	Use appropriate tools and techniques to analyze data Develop descriptions, explanations, predictions and models using evidence Think critically to make the relationship between evidence and explanations Think logically to make the relationship between evidence and explanations
Students Grades 9-12:	----
Scientists:	Scientists develop explanations using observations (evidence) and . . . Good explanations are based on evidence from investigations. Scientific explanations emphasize evidence. . . . . . [I]t is normal for scientists to differ with one another about the interpretation of the evidence . . . being considered Scientific explanations . . . must abide by the rules of evidence Scientific explanations . . . must be consistent with experimental and observational evidence about nature. . . . methods and procedures that scientist used to obtain evidence must be clearly reported to enhance opportunities for further investigation*

*See Appendix A for page references.

Table 8: Questioning Abilities in the *NSES*

Adults:	. . . Find or determine answers to questions derived from curiosity about everyday experience
Students Grades K-4:	Ask questions about objects, organisms, and events in the environment
Students Grades 5-8:	Identify questions that can be answered through scientific investigations
Students Grades 9-12:	Identify questions and concepts that guide scientific investigations
Scientists:	Asking questions and querying other scientists' explanations is part of scientific inquiry . . . Ask questions about the results of other scientists' work*

*See Appendix A for page references.

Table 9: Thematic Literacy Groups for Reasoning and Communication Components in the *Curriculum and Evaluation Standards for School Mathematics*

Group 1:	**Reflection and Clarification**
K - 4	reflect on and clarify their thinking about mathematical ideas and situations
5 - 8	reflect on and clarify their own thinking about mathematical ideas and situations
9 - 12	reflect upon and clarify their thinking about mathematical ideas and relationships
Group 2:	**Attitude or Affect**
K - 4	realize that representing, discussing, reading, writing, and listening to mathematics are a vital part of learning and using mathematics
5 - 8	appreciate the value of mathematical notation and its role in the development of mathematical ideas
9 - 12	appreciate the economy, power, and elegance of mathematical notation and its role in the development of mathematical ideas.
Group 3:	**Presentation**
eval	use mathematical vocabulary, notation, and structure to represent ideas, describe relationships, and model situations
eval	express mathematical ideas by speaking, writing, demonstrating, and depicting them visually
K - 4	relate physical materials, pictures, and diagrams to mathematical ideas
5 - 8	model situations using oral, written, concrete, pictorial, graphical and algebraic methods
9 - 12	express mathematical ideas orally and in writing
Group 4:	**Language**
K - 4	relate their everyday language to mathematical language and symbols
5 - 8	develop common understandings of mathematical ideas, including the role of definitions
9 - 12	formulate mathematical definitions and express generalizations discovered through investigations
Group 5:	**Critical Analysis**
eval	understand, interpret, and evaluate mathematical ideas that are presented in written, oral, or visual forms
K - 4	---
5 - 8	use the skills of reading, listening, and viewing to interpret and evaluate mathematical ideas; discuss mathematical ideas and make conjectures and convincing arguments
9 - 12	read written presentations of mathematics with understanding; ask clarifying questions related to mathematics they have read or heard about

Table 10: Actions and Types of Reasoning from NCTM Reasoning Standards

Section	Component	Reasoning Actions	Type of Reasoning
K-4	use patterns and relationships to analyze mathematical situations	analyze	----
	use models, know facts, properties and relationships to explain their thinking	explain	----
	justify their answers and solution processes	justify	----
	draw logical conclusions about mathematics	----	logical
5-8	understand and apply reasoning processes with special attention to spatial reasoning with proportions and graphs	---- proportional, graphical	general, spatial,
	make and evaluate mathematical conjectures and arguments	evaluate, conjecture	
	argue	----	
	validate their own thinking	validate	----
	recognize and apply deductive and inductive reasoning	----	deductive, inductive
	appreciate the pervasive use and power of reasoning as part of mathematics	----	general
9-12	follow logical arguments	argue	logical
	make and test conjectures	conjecture, test	----
	construct simple valid arguments	argue, validate	----
	judge the validity of arguments	argue, validate	----
	formulate counter-examples	counter	----
	construct proofs for mathematical assertions, including indirect proofs and proofs by induction	prove	deduction, induction, evaluation
	analyze situations to determine common properties and structures	analyze	----
	use reasoning to develop plausible arguments for mathematical statements	argue	general
	use proportional and spatial reasoning to solve problems	solve	proportional, spatial
	use inductive reasoning to recognize patterns and form conjectures	recognize, conjecture	inductive
	use deductive reasoning to verify conclusions, judge the validity of arguments, and construct valid arguments	verify, conclude, deductive	
	judge, validate, argue		

Table 11: Observable/Inferred Dimension and Generative/Evaluative Dimension with Sample Standards

	Observable	Inferred
Generate	Ask a question about objects, organisms and events in the environment. (NRC, 1996, p. 122) Raise questions about the world. (AAAS, 1993, p. 285) Formulate problems from everyday and mathematical situations. (NCTM, 1989, p. 23)	Think logically to make the relationship between evidence and explanations. (NRC, 1996, p. 145) Use and correctly interpret relational terms such as . . . correlates with and causes. (AAAS, 1993, p. 297) Draw logical conclusions. (NCTM, 1989, p. 26)
Evaluate	Evaluate completed technological designs or products by suggesting improvements. (NRC, 1996, p. 165) Judge whether measurements and computations of quantities are reasonable in a familiar context by comparing them to typical values. (AAAS, 1993, p. 290) Use estimation to check the reasonableness of answers. (NCTM, 1989, p. 94)	Analyze alternative explanations and predictions. (NRC, 1996, p. 148) Judge whether results make sense and are useful. (AAAS, 1993, p. 36) Evaluate mathematical conjectures and arguments. (NCTM, 1989, p. 81)

APPENDIX A: *National Science Education Standards* (NRC, 1996):
Scientific Communication and Reasoning
Abilities, Concepts and Principles

Unifying Concepts and Processes K-12

ABILITIES	CONCEPTS and PRINCIPLES
	evidence Evidence consists of observations and data on which to base scientific explanations. Using evidence to understand interactions allows individuals to predict changes in natural and designed systems. (p. 117)
	explanation Scientific explanations incorporate existing scientific knowledge and new evidence from observations, experiments, or models into internally consistent, logical statements. Different terms such as "hypothesis," "model," "law," "principle," "theory," and "paradigm" are used to describe various types of scientific explanations. As students develop and as they understand more science concepts and processes, their explanations should become more sophisticated. That is, their scientific explanations should more frequently include a rich scientific knowledge base, evidence of logic, higher levels of analysis, greater tolerance of criticism and uncertainty, and a clearer demonstration of the relationship between logic, evidence, and current knowledge. (p. 117)

Kindergarten - Grade 4

ABILITIES	CONCEPTS and PRINCIPLES
ask a question *ASK A QUESTION ABOUT OBJECTS, ORGANISMS, AND EVENTS IN THE ENVIRONMENT* This aspect of the standard emphasizes students asking questions that they can answer with scientific knowledge, combined with their own observations. Students should answer their questions by seeking information from reliable sources of scientific information and from their own observations and investigations. (p. 122)	
construct a reasonable explanation *USE DATA TO CONSTRUCT A REASONABLE EXPLANATION* This aspect of the standard emphasizes the students' thinking as they use data to formulate explanations. Even at the earliest grade levels, students should learn what constitutes evidence and judge the merits or strength of the data and information that will be used to make explanations. After students propose an explanation, they will appeal to the knowledge and evidence they obtained to support their explanations against scientific knowledge, experiences and observation of others (p.122)	**Scientists develop explanations** using observations (evidence) and what they already know about the world (scientific knowledge). **Good explanations are based on evidence** from investigations (p. 123)
communicate *COMMUNICATE INVESTIGATIONS AND EXPLANATIONS* Students should begin developing the abilities to communicate, critique, and analyze their work and the work of other students. This communication might be spoken or drawn as well as written. (p. 122)	Scientists make the results of their investigations public -- they **describe** the investigations in ways that enable others to repeat the investigations. (p. 123)

Kindergarten - Grade 4

ABILITIES	CONCEPTS and PRINCIPLES
identify *IDENTIFY A SIMPLE PROBLEM* Students should make proposal to build something or get something to work better: they should be able to describe and communicate their ideas. Students should recognize that designing a solution might have constraints, such as cost, materials, time, space, or safety. (p.137)	
propose *PROPOSE A SOLUTION* Students should make proposals to build something or get something to work better; they should be able to describe and communicate their ideas. Students should recognize that designing a solution might have constraints, such as cost, materials, time, space, or safety. (p.137)	
communicate *COMMUNICATE A PROBLEM, DESIGN AND SOLUTION* Student abilities should include oral, written, and pictorial communication of the designed process and product. The communication might be show and tell, group discussions, short written reports or pictures, depending on the students' abilities and the designed project. (p. 138)	
evaluate *EVALUATE A PRODUCT OR DESIGN* Students should evaluate their own results or solutions to problems as well as those of other children by considering how well a product or design met the challenge to solve a problem. When possible students should use measurements and include constraints and other criteria in their evaluations. They should modify designs based on the results of evaluations. (p. 137)	Scientists review and **ask questions** about the results of other scientists' work. (p. 123)

Grade 5 - Grade 8

ABILITIES	CONCEPTS and PRINCIPLES
identify questions *IDENTIFY QUESTIONS THAT CAN BE ANSWERED THROUGH SCIENTIFIC INVESTIGATIONS* Students should develop the ability to refine and refocus broad and ill-defined questions. An important aspect of this ability consists of students' ability to clarify questions and inquiries and direct them towards objects and phenomena that can be described, explained, or predicted by scientific investigations. Students should develop the ability to identify their questions with scientific ideas, concepts, and quantitative relationships that guide investigations. (p. 145)	
analyze *USE APPROPRIATE TOOLS AND TECHNIQUES TO ANALYZE DATA* The use of tools and techniques, including mathematics, will be guided by the question asked and the investigations students design. The use of computers for the collection, summary, and display of evidence is part of this standard. Students should be able to access, gather, store, retrieve, and organize data, using hardware and software designed for these purposes. (p. 145)	
interpret *USE APPROPRIATE TOOLS AND TECHNIQUES TO INTERPRET DATA* Same as Above. (p. 145)	

Grade 5 - Grade 8

ABILITIES	CONCEPTS and PRINCIPLES
using evidence *DEVELOP DESCRIPTIONS, EXPLANATIONS, PREDICTIONS AND MODELS USING EVIDENCE* Students should base their explanation on what they observed and as they develop cognitive skills, they should be able to differentiate explanation from description -- providing causes for effects and establishing relationships based on evidence and logical argument. This standard requires a subject matter knowledge base so these students can effectively conduct investigations, because developing explanations establishes connections between the content of science and the contexts within which students develop new knowledge. (p. 145)	Scientists **formulate and test their explanations** of nature using observation, experiments, and **theoretical and mathematical models**. Although all scientific ideas are tentative and subject to change and improvement in principle, for most major ideas in science, there is much experimental and observational confirmation. Those ideas are not likely to change greatly in the future. Scientists do and have changed their ideas about nature when they encounter new experimental evidence that does not match their existing explanations.; (p. 171) Scientific explanations emphasize **evidence**, have **logically consistent arguments**, and use scientific principles, models and theories. The scientific community accepts and uses such explanations until displaced by better scientific ones. When such displacement occurs, science advances; (p. 148)
Think critically *THINK CRITICALLY TO MAKE THE RELATIONSHIP BETWEEN EVIDENCE AND EXPLANATIONS* Thinking critically about evidence includes deciding what evidence should be used and accounting for anomalous data. Specifically students should be able to review data from a simple experiment, summarize the data and form a logical argument about the cause-and-effect relationships in the experiment. Students should begin to state some explanations in terms of the relationship between two or more variables. (p. 145, 148)	
Think logically *THINK LOGICALLY TO MAKE THE RELATIONSHIP BETWEEN EVIDENCE AND EXPLANATIONS* Same as Above. (p. 145)	Science requires different abilities, depending on such factors as the field of study and type of inquiry. Science is very much a human endeavor, and the work of science relies on basic human qualities, such as **reasoning**, insight, energy, skill, and creativity -- as well as on scientific habits of mind, such as intellectual honesty, tolerance of ambiguity, skepticism, and openness to new ideas; (p. 170)

Grade 5 - Grade 8

ABILITIES	CONCEPTS and PRINCIPLES
analyze *ANALYZE ALTERNATIVE EXPLANATIONS AND PREDICTIONS* Students should develop the ability to listen to and respect the explanations proposed by other students. They should remain open to and acknowledge different ideas and explanations, be able to accept the skepticism of others, and consider alternative explanations. (p. 148)	In areas where active research is being pursued and in which there is not a great deal of experimental or observational evidence and understanding, it is normal for scientists to differ with one another about the **interpretation of the evidence or theory** being considered. Different scientists might **publish** conflicting experimental results or might **draw different conclusions** from the same data. Ideally, scientists acknowledge such conflict and work towards finding evidence that will resolve the disagreement; (p. 171)
communicate *COMMUNICATE SCIENTIFIC PROCEDURES AND EXPLANATIONS* With practice, students should become competent at communicating experimental methods, following instructions, describing observations, summarizing the results of other groups, and telling other students about investigations and explanations. (p. 148)	Women and men of various social and ethnic backgrounds -- and with diverse interests, talents, qualities, and motivations -- engage in the activities of science, engineering, and related fields such as the health professions. Some scientists work in teams, and some work alone, but all **communicate** extensively with others.; (p. 170)

Grade 5 - Grade 8

ABILITIES	CONCEPTS and PRINCIPLES
evaluate *EVALUATE COMPLETED TECHNOLOGICAL DESIGNS OR PRODUCTS* Students should use criteria relevant to the original purpose or need, consider a variety of factors that might affect acceptability and suitability for intended users or beneficiaries and develop measures of quality with respect to such criteria and factors; they should also suggest improvements and for their own products, try proposed modifications. (p. 165)	It is part of scientific inquiry to **evaluate the results** of scientific investigations, experiments, observations, theoretical models, and the explanations proposed by other scientists. Evaluation includes reviewing the experimental procedures, examining the evidence, **identifying faulty reasoning**, pointing out statements that go beyond the evidence, and **suggesting alternative explanations** for the same observations. Although scientists may disagree about explanations of phenomena, about interpretations of data, or about the value of rival theories, they do agree that questioning, response to criticism, and **open communication** are integral to the process of science. As scientific knowledge evolves, major disagreements are eventually resolved through such **interactions between scientists**. (p. 171) Science advances through legitimate skepticism. **Asking questions and querying** other scientists' explanations is part of scientific inquiry. Scientists **evaluate the explanations** proposed by other scientists by examining evidence, comparing evidence, **identifying faulty reasoning**, pointing out statements that go beyond the evidence, and **suggesting alternative explanations** for the same observations. (p. 148)
communicate *COMMUNICATE THE PROCESS OF TECHNOLOGICAL DESIGN* Students should review and describe in a completed piece of work and identify the stages of problem identification, solution design, implementation, and evaluation. (p. 166)	

National Science Education Standards
Scientific Communication and Reasoning
Abilities, Concepts and Principles

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
identify *IDENTIFY QUESTIONS AND CONCEPTS THAT GUIDE SCIENTIFIC INVESTIGATIONS* Students should formulate a testable hypothesis and demonstrate the logical connections between the scientific concepts guiding a hypothesis and the design of an experiment. They should demonstrate appropriate procedures, a knowledge base, and conceptual understanding of scientific investigations. (p. 175)	
use technology *USE TECHNOLOGY TO IMPROVE COMMUNICATIONS* A variety of technologies, such as hand tools, measuring instruments, and calculators, should be an integral component of scientific investigations. The use of computers for the collection, analysis, and display of data is also a part of this standard. Mathematics plays an essential role in all aspects of an inquiry. For example, measurement is used for posing questions, formulas are used for developing explanations, and charts and graphs are used for communicating results. (p. 175)	
use mathematics *USE MATHEMATICS TO IMPROVE COMMUNICATIONS* Same as Above. (p. 175)	Mathematics is essential in scientific inquiry. Mathematical tools and models guide and improve the posing of questions, gathering data, **constructing explanations and communicating results**.; (p. 176)

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
using evidence *FORMULATE AND REVISE SCIENTIFIC EXPLANATIONS AND MODELS USING EVIDENCE* Student inquiries should culminate in formulating an explanation or model. Models should be physical, conceptual, and mathematical. In the process of answering the questions, the students should engage in discussions and arguments that result in the revision of their explanations. These discussions should be based on scientific knowledge, the use of logic, and evidence from their investigation. (p. 175)	Scientists usually inquire about how physical, living, or designed systems function. Conceptual principles and knowledge guide scientific inquiries. Historical and current scientific knowledge influence the design and interpretation of investigations and the **evaluation of proposed explanations** made by other scientists; (p. 176) Scientists in different disciplines **ask different questions**, use different methods of investigation, and accept different types of evidence **to support their explanations**. Many scientific investigations require the contributions of individuals from different disciplines, including engineering. New disciplines of science, such as geophysics and biochemistry often emerge at the interface of two older disciplines.; (p. 192)
using logic *FORMULATE AND REVISE SCIENTIFIC EXPLANATIONS AND MODELS USING LOGIC* Same as Above. (p. 175)	**Scientific explanations** must adhere to criteria such as: as proposed explanations must **be logically consistent**; it must abide by the rules of evidence; it must be open to questions and possible modification; and it must be based on historical and current scientific knowledge.; (p. 176) **Scientific explanations** must meet certain criteria. First and foremost, they must be consistent with experimental and observational evidence about nature, and must make **accurate predictions**, when appropriate, about systems being studied. They should also be **logical**, respect the rules of evidence, be open to criticism, report methods and procedures, and **make knowledge public**, Explanations on how the natural world changes based on myths, personal beliefs, religious values, mystical inspiration, superstition, or authority may be personally useful and socially relevant, but they are not scientific.; (p. 201)

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
analyze *ANALYZE ALTERNATIVE EXPLANATIONS* This aspect of standard emphasizes the critical abilities of analyzing an argument by reviewing current scientific understanding, weighing the evidence, and examining the logic so as to decide which explanations and models are best. In other words, although there may be several plausible explanations, they do not all have equal weight. Students should be able to use scientific criteria to find the preferred explanations. (p. 175)	
communicate *COMMUNICATE A SCIENTIFIC ARGUMENT* Students in school science programs should develop the abilities associated with accurate and effective communication. These include writing and following procedures, expressing concepts, reviewing information, summarizing data, using language appropriately, developing diagrams and charts, explaining statistical analysis, speaking clearly and logically constructing a reasoned argument and responding appropriately to critical comments. (p. 176)	Results of scientific inquiry -- new knowledge and methods -- emerge from different types of investigations and **public communication** among scientists. **In communicating and defending results** of scientific inquiry, **arguments must be logical** and demonstrate connections between natural phenomena, investigations, and the historical body of scientific knowledge. In addition, the methods and procedures that scientists used to obtain evidence must be clearly reported to enhance opportunities for further investigation. (p. 176)
defend *DEFEND A SCIENTIFIC ARGUMENT* Same as Above. (p. 176)	
choose *CHOOSE BETWEEN ALTERNATIVE SOLUTIONS* Students should demonstrate thoughtful planning for a piece of technology or technique. Students should be introduced to the roles of models and simulations in these processes. (p. 192)	
evaluate *EVALUATE THE SOLUTION AND ITS CONSEQUENCES* Students should test any solution against the needs and criteria it was designed to meet. At this stage, new criteria not originally considered may be reviewed. (p. 192)	Individuals and society must decide on proposals involving new research and the introduction of new technologies into society. Decisions involve **assessment of alternatives, risks, costs, and benefits** and consideration of who bears them. Students should understand the appropriateness and value of basic questions "What can happen?" What are the odds?" and "How do scientist and engineers know what will happen?" (p. 199)

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
communicate *COMMUNICATE THE PROBLEM, PROCESS, AND SOLUTION* Students should present their results to students, teachers, and others in a variety of ways, such as orally, in writing, and in other forms -- including models, diagrams, and demonstrations. (p. 192)	Technological knowledge is often not made public because of patents and the financial potential of the idea or invention. Scientific knowledge is made public through **presentations** at professional meetings and **publications** in scientific journals; (p. 193) Scientists have ethical traditions. Scientists value **peer reviews**, truthful **reporting** about the methods and outcomes of investigations, and **making public** the results of work. Violations of such norms do occur, but scientists responsible for such violations are censured by their peers. (p. 200-201)

APPENDIX B: *National Science Education Standards* (NRC, 1996)
Scientific Communication and Reasoning
Science Teaching Standards and other Professional Standards

Standard A **(4:0 Relevant)**
Teachers of science plan an inquiry-based science program for their students. In doing this, teachers--

None Relevant
(p. 30)

Standard B **(5:1 Relevant)**
Teachers of science guide and facilitate learning. In doing this teachers--

Orchestrate **discourse** among students about scientific ideas.
(p. 32)

Standard C **(5:0 Relevant)**
Teachers of science engage in ongoing assessment of their teaching and on student learning. In doing this, teachers--

None Relevant
(p. 37)

Standard D **(6:0 Relevant)**
Teachers of science design and manage learning environments that provide students with the time, space, and resources needed for learning science. In doing this, teachers--

None Relevant
(p. 43)

Standard E **(5:3 Relevant)**
Teachers of science develop communities of science learners that reflect the intellectual rigor of scientific inquiry and the attitude and social values conducive to science learning. In doing this, teachers--

Enable students to have a significant voice in decisions about the content and context of their work and require students to **take responsibility for the learning of all members** of the community;
Nurture **collaboration among students**;
Structure and facilitate ongoing **formal and informal discussion** based on a shared understanding of rules of **scientific discourse**;
(p. 45)

Standard F **(3:0 Relevant)**
Teachers of science actively participate in the ongoing planning and development of the school science program. In doing this, teachers--

None Relevant
(p. 51)

The Standards for Professional Development for Teachers of Science were analyzed and found to have none relevant to reasoning and communication for students. These standards all generally apply to expectations for teaching, not expectations of students.

The *Assessment in Science Education Standards*, *Science Education Program Standards*, and *Science Education System Standards* were all found to be too general and did not deal with specific expectations of students.

APPENDIX C: American Association for the Advancement of Science *Benchmarks for Science Literacy* (AAAS, 1993)
Scientific Reasoning and Communication
Abilities, Concepts and Principles

Grade K - Grade 2

ABILITIES	CONCEPTS and PRINCIPLES
Raise questions about the world around them and be willing to seek answers to some of them by making careful observations and trying things out. (p. 285)	When trying to build something or to get something to work better, it usually helps to follow directions if there are any or **to ask someone** who has done it before for suggestions. (p. 44)
Use whole numbers and simple, everyday fractions in ordering, counting, identifying, measuring, and **describing** things and experiences.; (p. 290)	Shapes such as circles, squares, and triangles can be used to **describe** many things that can be seen. (p. 223)
	Numbers and shapes can be used to **tell about things**. (p. 36)
Readily give the sums and differences of single-digit numbers in familiar contexts where the operation makes sense to them and they can **judge the reasonableness of the answer**. (p. 290)	
Explain to other students how they go about solving numerical problems. (p. 290)	
Assemble, **describe**, take apart and reassemble constructions using interlocking blocks, erector sets, and the like. (p. 293)	**Describing things** as accurately as possible is important in science because it enables people to compare their observations with those of others. (p. 10)
Describe and compare things in terms of number, shape, texture, size, weight, color, and motion; (p. 296)	One way to **describe** something is to say how it is like something else. (p. 268)
Draw pictures that correctly portray at least some features of the thing being described. (p. 296)	Simple **graphs** can help **to tell** about observations. (p. 211)
Ask "How do you know?" in appropriate situations and **attempt reasonable** answers when others ask them the same question. (p. 298)	People are more likely to believe your ideas if you can give **good reasons** for them. (p. 232)
	In doing science, it is often helpful to work with a team and to **share findings** with others. All team members should reach their own individual conclusions, however, about what the findings mean. (p. 15)

Grade K - Grade 2

ABILITIES	CONCEPTS and PRINCIPLES
	People can learn from each other **by telling and listening**, showing and watching, and imitating what others do. (p. 140) **Talking to someone** (a friend, relative, teacher, or counselor) may help people understand their feelings and problems and what to do about them. (p. 148)

Grade 3 - Grade 5

ABILITIES	CONCEPTS and PRINCIPLES
Offer reasons for their findings and consider reasons suggested by others. (p. 286)	Scientists do not pay much attention to claims about how something they know about works unless the claims are **backed up with evidence** that can be confirmed and with a **logical argument**. (p. 11) Human beings can use the memory of their past experiences **to make judgements** about situations. (p. 140) People can learn about others from direct experience, from the mass communications media, and from **listening** to other people talk about their work and their lives. People also sometimes imitate people -- or characters -- in the media. (p. 154) **Communicating** the different points of view in a dispute can often help people to find a satisfactory compromise. (p. 172)
Judge whether measurements and computations of quantities such as length, area, volume, weight, or time are **reasonable** in a familiar context by comparing them to typical values.; (p. 290)	In using mathematics, choices have to be made about what operations will give the best results. Results **should always be judged by whether they make sense and are useful**. (p. 36)
State the purpose of each step in a calculation. (p. 290).	**Clear communication** is an essential part of doing science. It enables scientists to inform others about their work, expose their ideas to criticism by other scientists, and stay informed about scientific discoveries around the world. (p. 16)
Keep a notebook that **describes** observations made, carefully distinguishes actual observations from ideas and speculations about what was observed, and is understandable weeks or months later. (p. 393)	Numbers and shapes -- and operations on them -- help to **describe and predict things** about the world around us.; (p. 36)
Write instructions that others can follow in carrying out a procedure: (p. 296)	

Grade 3 - Grade 5

ABILITIES	CONCEPTS and PRINCIPLES
Make sketches to aid in explaining procedures or ideas; (p. 296)	
Use numerical data in **describing** and comparing objects and events. (p. 296)	Many objects **can be described** in terms of simple plane figures and solids. Shapes can be compared in terms of concepts such as parallel and perpendicular, congruence and similarity, and symmetry. Symmetry can be found by reflection, turns, or slides. (p. 223)
Buttress their statements with facts found in books, articles, and databases, and **identify** the sources used and expect others to do the same. (p. 299)	**Scientists' explanations** about what happens in the world come partly from what they observe, partly from what they think. Sometimes scientists have different explanations for the same set of observations. That usually leads to their making more observations to resolve the differences; (p. 11)
	Reasoning can be distorted by strong feelings. (p. 232)
	Rules and laws can sometimes be changed by getting most of the people they affect to **agree to change them.** (p. 162)
	In making decisions, it helps to take time to **consider the benefits and drawbacks of alternatives.** (p. 165)
	People **have always tried to communicate** with one another. Signed and spoken language was one of the first inventions. Early forms of recording messages used markings on materials such as wood or stone; (p. 197)
	Communication involves coding and decoding information. In any language, both the sender and the receiver have to know the same code, which means that secret codes can be used to keep communication private; (p. 197)

Grade 6 - Grade 8

ABILITIES	CONCEPTS and PRINCIPLES
Use, **interpret,** and compare numbers in several equivalent forms such as integers, fractions, decimals and percents. (p. 291)	Scientists differ greatly in what phenomena they study and how they go about their world. Although there is no fixed set of steps that all scientists follow, scientific investigations usually involve the collection of relevant evidence, **the use of logical reasoning**, and the application of imagination in devising hypotheses and explanations to make sense of the collected evidence; (p. 12)
Organize information in simple tables and graphs and **identify** relationships they reveal.; (p. 297)	Some aspects or reasoning have fairly rigid rules for what makes sense; other aspects don't. If people have rules that always hold, and good information about a particular situation, then logic can help them figure out what is true about it. This **kind of reasoning** requires care in the use of key words such as *if, and, not, or, all,* and *some*. **Reasoning by similarities** can suggest ideas but can't prove them one way or the other.; (p. 233)
Read simple tables and graphs produced by others and **describe** in words what they show; (p. 297)	The human ability to shape the future comes from a capacity for generating knowledge an developing new technologies-- and for **communicating ideas** to others; (p. 55)
Find and **describe** locations on maps with rectangular and polar coordinates. (p. 297)	Mathematical statements can be used **to describe** how one quantity changes when another changes. Rates of change can be computed from differences in magnitudes and vice versa. (p. 219)

Grade 6 - Grade 8

ABILITIES	CONCEPTS and PRINCIPLES
Notice and **criticize the reasoning in arguments** in which (1) fact and opinion are intermingled so the conclusions do not follow logically from the evidence given, (2) an analogy is not apt, (3) no mention is made of whether the control groups are very much like the experimental group, or (4) all members of a group (such as teenagers or chemists) are implied to have nearly identical characteristics that differ from those of other groups. (p. 299)	When mathematicians use logical rules to work with representations of things, the results may or may not be valid for the things themselves. Using mathematics to solve a problem requires choosing what mathematics to use; probably making some simplifying assumptions, estimates, or approximations; doing computations; and then **checking to see whether the answer makes sense**. If an answer does not seem to make enough sense for its intended purpose, then any of these steps might have been inappropriate. (p. 37) When similar investigations give different results, **the scientific challenge is to judge whether the differences are trivial or significant**, and it often takes further studies to decide. Even with similar results, scientists may wait until an investigation has been repeated many times before accepting the results as correct. (p. 7) **Practical reasoning**, such as diagnosing or troubleshooting almost anything, may require many-step, branching logic. Because computers can keep track of complicated logic, as well as a lot of information, they are useful in a lot of problem-solving situations.; (p. 233) If more than one variable changes at the same time in an experiment, the outcome of the experiment may not be clearly attributable to any one of the variables. It may not always be possible to prevent outside variables from influencing the outcome of an investigation (or even to identify all of the variables), **but collaboration among investigations** can often lead to research designs that are able to deal with such situations. (p. 12)

ABILITIES	CONCEPTS and PRINCIPLES
	In research involving human subjects, the ethics of science require that potential subjects **be fully informed** about the risks and benefits associated with the research and of their right to refuse to participate. Science ethics also demand that scientists must not knowingly subject coworkers, students, the neighborhood, or the community to health or property risks without their prior knowledge and consent. Because animals cannot make informed choices, special care must be taken in using them in scientific research. (p. 17)
	Computers have become invaluable in science because they speed up and extend **people's ability** to collect, store, compile, and **analyze data**, prepare research reports, and **share data and ideas** with investigators all over the world. (p. 18)
	Language and tools enable human beings to learn complicated and varied things from others. (p. 142)
	Technology, especially in transportation and communication, is increasingly important in **spreading ideas**, values, and behavior patterns within a society and among different societies. New technology can change cultural values and social behavior. (p. 155)
	By the way they **depict the ideas and customs** of one culture, communications media may stimulate changes in others. (p. 163)
	Computer control of mechanical systems can be much quicker than human control. In situations where events happen faster than people can react, there is little choice but to rely on computers. Most complex systems still require human oversight, however to **make certain kinds of judgements** about the readiness of the parts of the system (including the computers) and the system as a whole to operate properly, to react to unexpected failures, and to **evaluate** how well the system is serving its intended purpose. (p. 202-203)

ABILITIES	CONCEPTS and PRINCIPLES
	In medicine, as in other fields of science, discoveries are sometimes made unexpectedly, even by accident. **But knowledge and creative insight are usually required to recognize the meaning of the unexpected.** (p. 257)

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
Find answers to problems by substituting numerical values in simple algebraic formulas and **judge whether the answer is reasonable** by reviewing the process and checking against typical values. (p. 291)	In the short run, new ideas that do not mesh well with mainstream ideas in science often encounter vigorous criticism. In the long run, theories are judged by how they fit with other theories, **the range of observations they explain, how well they explain observations**, and how effective they are in predicting new findings. (p. 13)
Make and **interpret** scale drawings; (p. 297)	
Write clear, step-by-step instructions for conducting investigations, operating something, or following a procedure. (p. 297)	Some work in mathematics is much like a game -- **mathematicians choose an interesting set of rules** and then play according to those rules to see what can happen. The more interesting the results, the better. The only limit on the set of rules is that they should not contradict one another. (p. 38) Written records and photographic and electronic devices enable human beings **to share, compile, use, and misuse great amounts of information** and misinformation. No other species uses such technologies. (p. 130)
Choose appropriate summary statistics to **describe** group differences, always indicating the spread of data as well as the data's central tendencies.; (p. 297)	
Describe spatial relationships in geometric terms such as perpendicular, parallel, tangent, similar, congruent, and symmetrical; (p. 297)	Mathematics provides a precise language for science and **technology-to describe objects and events**, to characterize relationships between variables, and to **argue logically.** (p. 33) Geometric shapes and relationships can be **described** in terms of symbols and numbers -- and vice versa. For example, the position of any point on a surface can be specified by two numbers; a graph represents all the values that satisfy an equation; and if two equations have to be satisfied at the same time, the values that satisfy them both will be found where their graphs intersect. (p. 225)

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
Use and correctly **interpret** relational terms such as *if, then, and, or, sufficient, necessary, some, every, not, correlates with,* and *causes.*; (p. 297)	
Participate in group discussions on scientific topics by restating or summarizing accurately what others have said, asking for clarification or elaboration, and expressing **alternative positions**.; (p. 297)	
Use tables, charts, and graphs **in making arguments** and claims in oral and written presentations. (p. 297)	Tables, graphs, and symbols are alternative ways of **representing data** and relationships that can be translated from one to another. (p. 221) Graphs and equations are useful (and often equivalent) ways for depicting and **analyzing** patterns of change. (p. 275)
Notice and **criticize** arguments based on the faulty, incomplete, or misleading use of numbers, such as in instances when (1) average results are reported, but not the amount of variation around the average, (2) a percentage or fraction is given, but not the total sample size (as in "9 out of 10 dentists recommend . . ."), (3) absolute and proportional quantities are mixed (as in "3,400 more robberies in our city last year, whereas other cities had an increase of less than 1%"), or (4) results are reported with overstated precision (as in representing 13 out of 19 students as 68.42%).; (p. 300)	Scientists in any one research group tend to see things alike, so even groups of scientists may have trouble being entirely objective about their methods and findings. For that reason, scientific teams are expected to seek out the possible sources of bias in the design of their investigations and in their data analysis. **Checking each other's results and explanations** helps, but that is no guarantee against bias; (p. 13)
Insist that the critical assumptions behind any line of reasoning be made **explicit** so that the validity of the position being taken -- whether one's own or that of others -- can be **judged**.; (p. 300)	The strongly held traditions of science, including its commitment to **peer review** and publication, serve to keep the vast majority of scientists well within the bounds of ethical professional behavior. Deliberate deceit is rare and likely to be exposed sooner or later by the scientific enterprise itself. When violations of these scientific ethical traditions are discovered, they are strongly condemned by the scientific community, and the violators then have difficulty regaining the respect of other scientists. (p. 20) The **reasonableness** of the result of a computation can be estimated from what the inputs and operations are. (p. 221)

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
Suggest alternative ways of explaining data and criticize arguments in which data, explanations, or conclusions are represented as the only ones worth consideration, with no mention of other possibilities. Similarly, suggest alternative trade-offs in decisions and designs and criticize those in which major trade-offs are not acknowledged. (p. 300)	There are different traditions in science about what is investigated and how, but they all have in common certain **basic beliefs about the value of evidence, logic, and good arguments.** And there is agreement that progress in all fields of science depends on intelligence, hard work, imagination, and even chance; (p. 13) **In deciding among alternatives,** a major question is who will receive the benefits and who (not necessarily the same people) will bear the costs. (p. 166) To be convincing, **an argument needs to have both true statements and valid connections among them**. Formal logic is mostly about connections among statements, not about whether they are true. People sometimes use poor logic even if they begin with true statements, and sometimes they use logic that begins with untrue statements.; (p. 234) Current ethics in science hold that research involving human subjects may be conducted only **with informed consent** of the subjects, even if this constraint limits some kinds of potentially important research or influences the results. When it comes to participation in research that could pose risks to society, most scientists believe that a decision to participate or not is a matter of personal ethics rather than professional ethics.; (p. 19) **Risk analysis** is used to minimize the likelihood of unwanted side effects of a new technology. The public perception of risk may depend, however, on psychological factors as well as scientific ones. (p. 52) **Logic requires a clear distinction among reasons**: **A reason** may be *sufficient* to get a result, but perhaps is not the only way to get there; or, a reason my be *necessary* to get the result, but it may not be enough by itself; some reasons may be both sufficient and necessary.; (p. 234)

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
	Wherever a general rule comes from, logic can be used in testing how well it works. **Proving** a generalization to be false (just one exception will do) is easier than proving it to be true (for all possible cases). Logic may be of limited help in finding solutions to problems if one isn't sure that general rules always hold or that particular information is correct; most often, one has to deal with probabilities rather than certainties.; (p. 234) Understanding how things work and **designing solutions to problems** of almost any kind can be facilitated by systems analysis. In defining a system, it is important to specify its boundaries and subsystems, indicate its relation to other systems, and identify what its input and its output are expected to be. (p. 266)

APPENDIX D: NCTM *Curriculum and Evaluation Standards* (NCTM, 1989): Mathematics Communication and Reasoning Abilities, Concepts and Principles

Kindergarten -Grade 4

ABILITIES	CONCEPTS and PRINCIPLES
verify and interpret results with respect to the original problem; (p. 23)	
formulate problems from everyday and mathematical situations; (p. 23)	
reflect on and **clarify** their thinking about mathematical ideas and situations; (p. 26)	
relate physical materials, pictures, and diagrams to mathematical ideas; (p. 26)	
relate their everyday language to mathematical language and symbols; (p. 26)	realize that **representing, discussing, reading, writing, and listening** to mathematics are a vital part of learning and using mathematics; (p. 26)
draw logical conclusions about mathematics; (p. 29)	
use models, known facts, properties, and relationships **to explain** their thinking; (p. 29)	
justify their answers and solution processes; (p. 29)	
use patterns and relationships **to analyze** mathematical situations; (p. 29)	
relate various **representations** of concepts or procedures to one another; (p. 32)	
determine the reasonableness of results; (p. 36)	
interpret the multiple uses of numbers encountered in the real world; (p.38)	
develop meaning for the operations by **modeling and discussing** a rich variety of problem situations; (p. 41)	
relate the **mathematical language and symbolism** of operations to problem situations and **informal language**; (p. 41)	
model, explain, and develop reasonable proficiency with basic facts and algorithms; (p. 44)	
select and use computation techniques appropriate to specific problems and **determine if the results are reasonable;** (p. 44)	

Kindergarten -Grade 4

ABILITIES	CONCEPTS and PRINCIPLES
describe, model, draw, and classify shapes; (p. 48)	
investigate and **predict** the results of combining, subdividing, and changing shapes; (p. 48)	
collect, organize, and **describe** data; (p. 54)	
construct, **read, and interpret** displays of data; (p. 54)	
formulate and solve problems that involve collecting and **analyzing** data; (p. 54)	
use models to relate fractions to decimals and to find equivalent fractions; (p. 57)	
use models to explore operations on fractions and decimals; (p. 57)	
recognize, **describe**, extend, and create a wide variety of patterns; (p. 60)	
represent and **describe** mathematical relationships; (p. 60)	
Explore the use of variables and **open sentences to express** relationships; (p. 60)	

NCTM *Curriculum and Evaluation Standards*
Mathematics Communication and Reasoning
Abilities, Concepts and Principles

Grade 5 - Grade 8

ABILITIES	CONCEPTS and PRINCIPLES
verify and interpret results with respect to the original problem situation; (p. 75)	
formulate problems from situations within and outside mathematics; (p. 75)	
model situations using oral, written, concrete, pictorial, graphical, and algebraic methods; (p. 78)	appreciate the value of **mathematical notation** and its role in the development of mathematical ideas; (p. 78)
reflect on and **clarify** their own thinking about mathematical ideas and situations; (p. 78)	
use the skills of reading, listening, and viewing to interpret and evaluate mathematical ideas; (p. 78)	
discuss mathematical ideas and **make conjectures and convincing arguments**; (p. 78)	develop **common understandings** of mathematical ideas, including the role of definitions; (p. 78)
recognize and **apply deductive and inductive reasoning**; (p. 81)	appreciate the pervasive use and **power of reasoning** as a part of mathematics; (p. 81)
understand and **apply reasoning** processes, with special attention to spatial reasoning and reasoning with proportions and graphs; (p. 81)	
make and **evaluate** mathematical **conjectures and arguments**; (p. 81)	
validate their own thinking; (p. 81)	
explore problems and **describe results** using graphical, numerical, physical, algebraic, and verbal mathematical models or representations; (p. 84)	
apply mathematical thinking and modeling to solve problems that arise in other disciplines, such as art, music, psychology, science, and business.; (p. 84)	
understand, **represent**, and use numbers in a **variety of equivalent forms** (integer, fraction, decimal, percent, exponential, and scientific notation) in real-world and mathematical problem situations; (p. 87)	
represent numerical relationships in one- and two-dimensional graphs; (p. 87)	

Grade 5 - Grade 8

ABILITIES	CONCEPTS and PRINCIPLES
develop, **analyze, and explain** procedures for computation and techniques for estimation; (p. 94)	
develop, **analyze, and explain** methods for solving proportions; (p. 94)	
use estimation to **check the reasonableness** of results.; (p. 94)	
describe, extend, **analyze** and create a wide variety of patterns; (p. 98)	
describe and represent relationships with tables, graphs, and rules; (p. 98)	
analyze functional relationships to **explain** how a change in one quantity results in a change in another; (p. 98)	
represent situations and number patterns with tables, graphs, verbal rules, and equations and explore the interrelationships of these representations; (p. 102)	
systematically collect, organize and **describe** data; (p. 105)	
construct, read, and **interpret** tables, charts, and graphs; (p. 105)	
make inferences and **convincing arguments** that are based on data analysis; (p. 105)	
evaluate arguments that are based on data analysis; (p. 105)	
make predictions that are based on experimental or theoretical probabilities; (p. 109)	
identify, **describe**, compare, and classify geometric figures; (p. 112)	
visualize and **represent** geometric figures with special attention to developing spatial sense; (p. 112)	
represent and solve problems using geometric models; (p. 112)	
estimate, make, and use measurements to **describe** and compare phenomena; (p. 116)	

NCTM *Curriculum and Evaluation Standards*
Mathematics Communication and Reasoning
Abilities, Concepts and Principles

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
recognize and **formulate** problems from situations within and outside mathematics; (p. 137)	
reflect upon and **clarify** their thinking about mathematical ideas and relationships; (p. 140)	
formulate mathematical definitions and express generalizations discovered through investigations; (p. 140)	
express mathematical ideas orally and in writing; (p. 140)	appreciate the economy, power, and elegance of **mathematical notation** and its role in the development of mathematical ideas; (p. 140)
read written presentations of mathematics with understanding; (p. 140)	
ask clarifying and extending questions related to mathematics they have read or heard about; (p. 140)	
make and **test** conjectures; (p. 143)	
formulate counter-examples; (p. 143)	
follow logical arguments; (p. 143)	
judge the validity of arguments; (p. 143)	
construct simple valid arguments; (p. 143)	
construct proofs for mathematical assertions, including indirect proofs and proofs by mathematical induction; (p. 143)	
recognize equivalent **representations** of the same concept; (p. 146)	
relate procedures of one **representation** to procedures on an equivalent **representation**; (p. 146)	
represent situations that involve variable quantities with expressions, equations, inequalities, and matrices; (p. 150)	

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
use tables and graphs as tools to **interpret** expressions, equations, and inequalities.; (p. 150)	
represent and analyze relationships using tables, verbal rules, equations, and graphs; (p. 154)	
translate among tabular, symbolic, and graphical **representations** of functions; (p. 154)	
analyze the effects of parameter changes on the graphs of functions.; (p. 154)	
interpret and draw three-dimensional objects; (p. 157)	
represent problem situations with **geometric models** and apply properties of figures; (p. 157)	
classify figures in terms of congruence and similarity and **apply** these relationships; (p. 157)	
deduce properties of figures using transformations and using coordinates.; (p. 161)	
analyze properties of Euclidean transformations and **relate** translations to vectors.; (p. 161)	
translate between synthetic and coordinate **representations**; (p. 161)	
deduce properties of figures using vectors.; (p. 161)	
use circular functions **to model** periodic real-world phenomena; (p. 163)	
solve trigonometric equations and **verify** trigonometric identities.; (p. 163)	
design a statistical experiment to study a problem, conduct the experiment, and **interpret and communicate** the outcomes; (p. 167)	
construct and draw inferences from charts, tables, and graphs that summarize data from real-world situations; (p. 167)	
test hypothesis using appropriate statistics.; (p. 167)	
create and **interpret** discrete probability distributions.; (p. 171)	

Grade 9 - Grade 12

ABILITIES	CONCEPTS and PRINCIPLES
describe, in general terms, the normal curve and use its properties to answer questions about sets of data that are assumed to be normally distributed; (p. 171)	
apply the concept of a random variable to generate and **interpret** probability distributions including binomial, normal, and chi square.; (p. 171)	
represent problem situations using discrete structures such as finite graphs, matrices, sequences, and recurrence relations; (p. 176)	
develop and **analyze** algorithms; (p. 176)	
represent and analyze finite graphs using matrices; (p. 176)	
represent and solve problems using linear programming and difference equations; (p. 176)	
determine maximum and minimum points of a graph and **interpret** the results in problem situations; (p. 180)	
analyze the graphs of polynomial, rational, radical, and transcendental functions; (p. 180)	
prove elementary theorems within various mathematical structures, such as groups and fields; (p. 184)	

Evaluation Standards K-12

ABILITIES	CONCEPTS and PRINCIPLES
present the same mathematical concept or procedures in **different contexts, formats**, and problem situations; (p. 196)	
ability to use mathematical language to **communicate ideas**; (p. 205)	
ability to **reason and analyze**; (p. 205)	confidence in using mathematics to solve problems, **to communicate ideas, and to reason**; (p. 233)
verify and interpret results; (p. 209)	
formulate problems; (p. 209)	
express mathematical ideas by **speaking, writing, demonstrating, and depicting them visually;** (p. 214)	
understand, **interpret, and evaluate** mathematical ideas that are presented in written, oral, or visual forms; (p. 214)	
use mathematical vocabulary, notation, and structure **to represent ideas, describe relationships, and model situations;** (p. 214)	
use reasoning to develop plausible arguments for mathematical statements; (p. 219)	inclination **to monitor and reflect** on their own thinking and performance.; (p. 233)
use deductive reasoning to verify conclusions, **judge the validity of arguments**, and **construct valid arguments**; (p. 219)	
analyze situations to determine common properties and structures; (p. 219)	
use inductive reasoning to recognize patterns and form conjectures; (p. 219)	
use proportional and spatial reasoning to solve problems; (p. 219)	
label, **verbalize,** and define concepts; (p. 223)	
use models, diagrams, and symbols to represent concepts; (p. 223)	
translate from one mode of **representation** to another; (p. 223)	

Evaluation Standards K-12

ABILITIES	CONCEPTS and PRINCIPLES
give reasons for the steps in a procedure; (p. 228)	
verify the results of procedures empirically (e.g., using models) or analytically ; (p. 228)	

Appendix E: *Professional Standards for Teaching Mathematics* (NCTM, 1991): Mathematics Communication and Reasoning Standards for Teaching Mathematics

Standard 1: Worthwhile Mathematical Tasks (Relevant 11:2)

The teacher of mathematics should pose tasks that are based on:

None Relevant

and that:

- call for problem formulation, problem solving, and mathematical reasoning;
- promote communication about mathematics; (p. 25)

Standard 2: The teachers's role in discourse (Relevant 7:4)

The teacher of mathematics should orchestrate discourse by:

- listening carefully to students' ideas;
- asking students to clarify and justify their ideas orally and in writing;
- deciding what to pursue in depth from among the ideas that students bring up during a discussion;
- deciding when and how to attach mathematical notation and language to students' ideas; (p. 35)

Standard 3: Students' Role in Discourse (Relevant 7:7)

The teacher of mathematics should promote classroom discourse in which students:

- listen to, respond to, and question the teacher and one another;
- use a variety of tools to reason, make connections, solve problems and communicate;
- initiate problems and questions;
- make conjectures and present solutions;
- explore examples and counter examples to investigate a conjecture;
- try to convince themselves and one another of the validity of particular representations, solutions, conjectures, and answers;
- rely on mathematical evidence and argument to determine the validity; (p. 45)

Standard 4: Tools for enhancing discourse (Relevant 7:6)

The teacher of mathematics, in order to enhance discourse, should encourage and accept the use of:

- concrete materials as models;
- pictures, diagrams, tables, and graphs;
- invented and conventional terms and symbols;
- metaphors, analogies, and stories;
- written hypotheses, explanations, and arguments;
- oral presentations and dramatizations (p. 52)

Standard 5: Learning Environment (Relevant 7:3)

The teacher of mathematics should create a learning environment that fosters the development of each student's mathematical power by:

None Relevant

and by consistently expecting and encouraging students to:

- work independently or collaboratively to make sense of mathematics;
- take intellectual risks by raising questions and formulating conjectures;
- display sense of mathematical competence by validating and supporting ideas with mathematical argument; (p.57)

Standard 6: Analysis of Teaching and learning (Relevant 7:0)

None Relevant (p. 63)

NCTM *Professional Standards for Teaching Mathematics*
Mathematics Communication and Reasoning
Standards for the Evaluation of the Teaching of Mathematics

Standard 1: The Evaluation Cycle (Relevant 3:0)
None Relevant
(p. 75)

Standard 2: Teachers as Participants in Evaluation (Relevant 3:0)
None Relevant
(p. 80)

Standard 3: Sources of Information (Relevant 6:0)
None Relevant
(p. 84)

Standard 4: Mathematical Concepts, Procedures, and Connections (Relevant 5:1)
Assessment of the teaching of mathematical concepts, procedures, and connections should provide evidence that the teacher--

- engages students in mathematical discourse that extends their understanding of mathematical concepts, procedures, and connections; (p. 89)

Standard 5: Mathematics as Problem Solving, Reasoning, and Communication (Relevant 5:5)
Assessment of the teaching of mathematics as a process involving problem solving, reasoning, and communication should provide evidence that the teacher--

- models and emphasizes aspects of problem solving, including formulating and posing problems, solving problems using different strategies, verifying and interpreting results, and generalizing solutions;
- demonstrates and emphasizes the role of mathematical reasoning;
- models and emphasizes mathematical communication using written, oral, and visual forms;
- engages students in tasks that involve problem solving, reasoning, and communication;
- engages students in mathematical discourse that extends their understanding of problem solving and their capacity to reason and communicate mathematically; (p. 95)

Standard 6: Promoting Mathematical Disposition (Relevant 3:1)
Assessment of a teacher's fostering of students' mathematical dispositions should provide evidence that the teacher-

- promotes students' confidence, flexibility, perseverance, curiosity, and inventiveness in doing mathematics through the use of appropriate tasks and by engaging students in mathematical discourse; (p. 104)

Standard 7: Assessing Students' Understanding of Mathematics (Relevant 5:0)
None relevant
(p. 110)

Standard 8: Learning Environments (Relevant 7:2)
Assessment of the teacher's ability to create a learning environment that fosters the development of teach students' mathematical power should provide evidence that the teacher--

- conveys the notion that mathematics is a subject to be explored and created both individually and in collaboration with others;
- encourages students to draw and validate their own conclusions; (p. 115)

NCTM *Professional Standards for Teaching Mathematics*
Mathematics Communication and Reasoning
Standards for the Professional Development of Teachers of Mathematics

Standard 1: Experiencing Good Mathematics Teaching (Relevant 7:2)
Mathematics and mathematics education instructors in preservice and continuing education programs should model good mathematics teaching by--

- enhancing mathematical discourse through the use of a variety of tools, including calculators, computers, and physical and pictorial models;
- creating learning environments that support and encourage mathematical reasoning and teachers' dispositions and abilities to do mathematics; (p. 127)

Standard 2: Knowing Mathematics and School Mathematics (Relevant 7:0)
None Relevant
(p. 132)

Standard 3: Knowing Students as Learners of Mathematics (Relevant 4:0)
None Relevant
(p. 144)

Standard 4: Knowing Mathematical Pedagogy (Relevant 5:0)
None Relevant
(p. 151)

Standard 5: Developing as a Teacher of Mathematics (Relevant 5:0)
None Relevant
(p. 160))

Standard 6: The Teacher's Role in Professional Development (Relevant 8:0)
None Relevant
(p. 168)

NCTM *Professional Standards for Teaching Mathematics*
Mathematics Communication and Reasoning
Standards for the Support and Development of Mathematics Teachers and Teaching

Standard 1: Responsibilities of Policy Makers in Government, Business, and Industry (Relevant 3:0)
None Relevant
(p. 179)

Standard 2: Responsibilities of Schools and School Systems (Relevant 9:0)
None Relevant
(p. 181)

Standard 3: Responsibilities of Colleges and Universities (Relevant 7:0)
None Relevant
(p. 184)

Standard 4: Professional Organizations' Responsibilities (Relevant 4:0)
None Relevant
(p. 186)

Please help us assess the quality of our research report series by completing and returning the questionnaire below:

NAME OF REPORT: **LITERACY IN THE NATIONAL SCIENCE AND MATHEMATICS STANDARDS: COMMUNICATION AND REASONING**

1. Your position:

____ elementary school teacher	___ state ed. agency staff	___ policy maker
____ middle school teacher	___ professional developer	___ researcher
____ high school teacher	___ school administrator	___ education writer
____ college teacher/professor	___ district administrator	other_____

2. Clarity

	Very well				Not at all	
a. The concepts in this report were clearly expressed.	1	2	3	4	5	N/A
b. This report was well organized.	1	2	3	4	5	N/A

3. Utility

a. Reading this report gave me new information or insight into teaching or learning.	1	2	3	4	5	N/A
b. This report addresses a current and important problem in education,	1	2	3	4	5	N/A
. . . and offers a solution to the problem.	1	2	3	4	5	N/A
. . . and/or helps the reader understand the problem from a different perspective.	1	2	3	4	5	N/A
c. I found the ideas and solutions offered in this report to be feasible given current realities of policy and practice.	1	2	3	4	5	N/A

4. Scholarship

a. The conclusions drawn in the report are						
. . . adequately supported by the research presented.	1	2	3	4	5	N/A
. . . fully grounded in theory.	1	2	3	4	5	N/A

5. Any other comments or suggestions regarding this report or additional research needs in the area of English and language arts teaching and learning are greatly appreciated.

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Please return this form to:

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